UK-INNOVATION RESEARCH CENTRE

The Economic Significance of the UK Science Base

A REPORT FOR THE CAMPAIGN FOR SCIENCE AND ENGINEERING

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The UK Innovation Research Centre (UK~IRC) is a joint venture between the Centre for Business Research (CBR) at the University of Cambridge and Imperial College Business School to further research and knowledge exchange on innovation policy practice. The UK~IRC is global in scope and involves a large-scale, multi-year research programme and a Knowledge Hub to engage with and inform policy-makers and practitioners about innovation research. The research programme explores open innovation, service innovation, online communities and innovation policy-making. A further stream of research focuses on the nature of university-industry links and the role of higher education in innovation systems. Through the Hub, our aim is to maximise the effect of the research on policy and practice, so as to help the UK face its social, environmental and economic challenges.

The Centre is co-funded through grant number RES-598-28-0001by the Department for Business, Innovation and Skills (BIS), the Economic and Social Research Council (ESRC), the National Endowment for Science, Technology and the Arts (NESTA and the Technology Strategy Board (TSB).

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Jonathan Haskel, Alan Hughes and Elif Bascavusoglu-Moreau

Abstract

This paper reports on some key indicators of the economic significance of the science base. We ask first what the effects of state funding of the science base are. In particular, we ask how state funding of the science base in the UK affects private sector involvement, including the R&D location decisions of multinational firms. We then ask how public science funding affects private sector productivity. We find evidence that public sector funding of science is both consistent with the "crowding in" of private sector investment in R&D and that its interaction with private sector R&D raises private sector productivity.

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Executive summary

1. Economists view knowledge as potentially generating spillovers, so that private investors cannot appropriate the full returns from their investment. Hence one approach to government policy is justified on market failure grounds due to the implied gap between private and social returns. This spillover argument in particular suggests subsidies are for “pure” research, whose value is likely to be much less appropriable than “applied” research. Other important and increasingly cited rationales for policy support are based on addressing system failures. They emphasise the difficulty of drawing simple distinctions between pure and applied research and that the process of moving from pure to applied is not linear but involves interactions between the two. These approaches instead emphasise the interrelationship and complementarity between applied and basic research and the need to foster connections between the private and public sectors to generate effective knowledge exchange and productive iteration between the two sectors. They also emphasise the “two faces” of private sector R&D, first in terms of advancing knowledge and second in enhancing the absorptive capacity of an organisation measured in terms of its ability to access, understand and apply the results of research carried out elsewhere.

2. The globalisation of the R&D process has weakened the spillover rationales. On the spillovers side, if pure research is internationally mobile then countries can economise by relying on other country subsidies. However, from a systems point of view domestic R&D enhances absorptive capacity and the ability to access understand and absorb external basic and applied research. Therefore to capture spillovers requires domestic R&D effort. Domestic pure research is then complementary to domestic applied research, and both may attract “sticky” domestic and inward R&D justifying national support for “pure” research.

3. This report touches on a number of these issues by examining three questions around the “science base” (by which we mean the Dual Support system of research-based state funding for universities via Quality Related Funding Council Sources (QR) and the Research Councils (RC) which covers all disciplines plus government spending on R&D in the form of public research laboratories and the like).

   a. how does state funding of the science base affect private sector involvement including the decisions of UK and foreign business R&D managers to locate investment in the UK?
   b. how does public science funding affect private sector productivity?

4. We examine the role of state funding of research in three ways. First, we document that universities that have higher research funding (via QR and RC) also generate more research income from other sources (e.g. charities, industry, overseas funding, central government) (controlling for other factors). This is consistent with complementarities between such funding sources and a “willingness to pay” indication of the value placed upon public sector research by the private sector.

5. Second, we explore this correlation further, by using individual level survey evidence of research grant-holders. This documents that research grant-holders are more likely than non-grant holders to be “outward-facing” in a number of contexts. First, they are more likely to have research applied in a commercial context and for that research to be in a general area of commercial interest. Second, they are more likely to have

taken out a patent, licensed research outputs, formed a spin-out company or started a consultancy than non-grant holders.

6. Third, we review existing literature on the link between the strength of the publicly funded science base and the international location of R&D labs. These decisions are affected by a host of factors, both economic and non-economic and it is hard to isolate them. Nonetheless, there is general evidence that multinational enterprise (MNE) investment location is affected by the quality of a nation's science base. The most compelling evidence specific to the UK is that pharmaceutical MNEs locate their labs near to highly-rated university Chemistry departments.

7. Finally, we document a statistically significant correlation between state support for research (in the form of research councils, QR funding and government research labs) and industry-level (total factor) productivity growth, using a data set of 7 UK industries, 1992-2007 (controlling for other factors). This correlation depends on industry-level research activity, measured by industry R&D intensity or industry co-operation with the universities and public sector research institutes. That is to say, the effect of research council spending on industry productivity interacts with industry research activity. This is consistent with two interpretations. First, it might be that research council funding is more applicable in some industries than others (manufacturing versus hotels for example) and industry R&D activity measures this. Second, it might be that the translation of publicly supported research into productivity requires the industry to conduct its own research to build "absorptive capacity". At this level of aggregation we are unable to distinguish between these two views. However other evidence suggests absorptive capacity is important, and also that the role of R&D in innovation and productivity varies by sector. Our results are consistent with the view that both effects are likely to be important.

8. Our conclusions are as follows:

First, we have shown that there is a wide variety of positive impact links between the science base and the private sector. Moreover, there appears to be a "crowding in" effect of public sector R&D on domestic and foreign R&D activities in the UK.

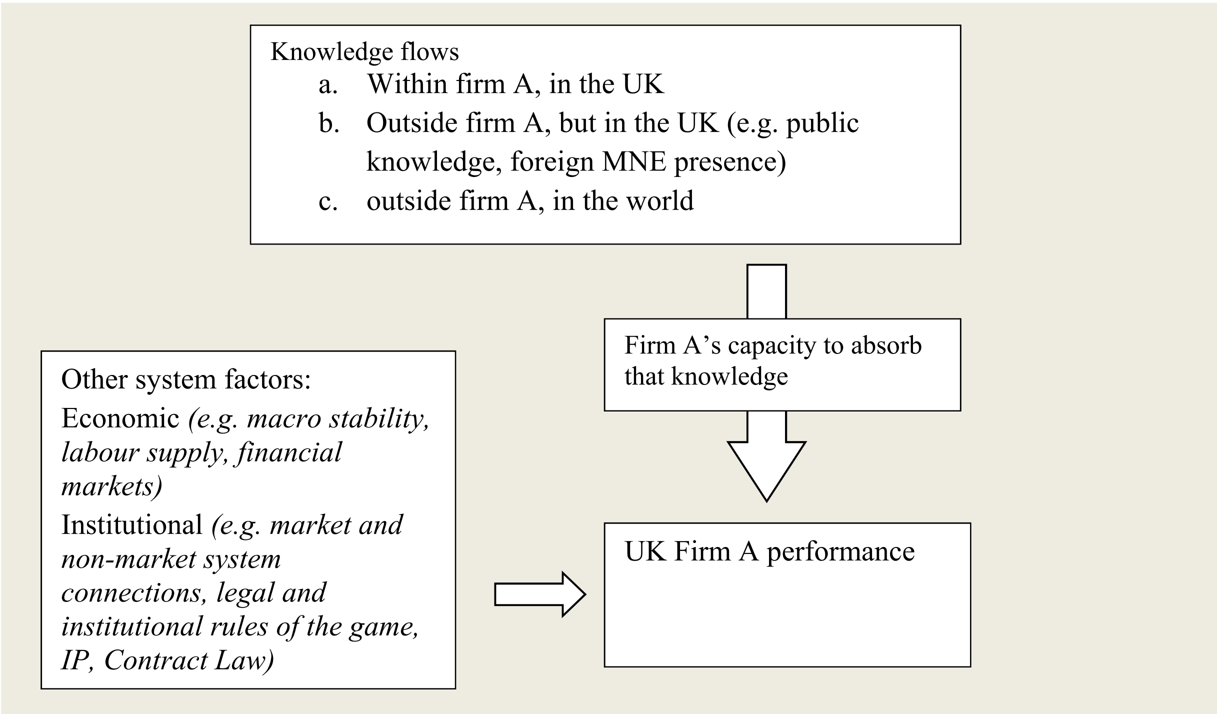
Second, a further and related key finding is that the link from the science budget to Total Factor Productivity (TFP) growth in an industry depends crucially on the R&D performance, or co-operation with the university sector, of the industry itself. This can be interpreted as the joint effect of an appropriate scaling of the public science budget to get the usable knowledge stock for each industry, and as a measure of the absorptive capacity of the industry. These can be taken with the results from the first part of the report to suggest a virtuous circle regarding private and public sector R&D.

These findings are consistent with a wide range of evidence suggesting a complementary relationship between industry and public sector R&D. Science and innovation policy is not and should not be seen as a zero-sum game in which they are substitutes.

1 Introduction

We seek in this report to understand better some of the aspects of public support for science and its effect on economic performance. Exhibit 1 sets out our approach to better understanding the performance of a firm in the UK and the way it is potentially affected by knowledge flows in the innovation system.

Exhibit 1: Broad Framework



Firms potentially benefit from three sources of knowledge, within the firm, outside the firm in the UK and outside the firm in the world. The benefits from such knowledge are mediated by their capacity to absorb that knowledge and the institutional and economic characteristics of the system in which the firms operate.

Public funding for science, therefore, impacts on performance in a number of ways. First, it directly affects knowledge creation in the UK outside the firm via funding universities (other policies such as the R&D tax credit might affect knowledge creation within the firm). This effect might be mediated by the magnitude of funding, the method of funding (e.g. via research councils, or other means such as QR via the Research Excellence Framework (REF)) and the continuity of funding. Second, it might affect outside firm knowledge via the choice of firms to locate in the UK, in particular locating their R&D labs. Third, it might or might not affect the firm's ability to absorb such knowledge via, for example, funding technology transfer and knowledge exchange activities.

The nature of each of these impacts will be mediated by system connections between the private sector and the science base, including overt co-operate funding of research and participation in various pathways to impact ranging from informal advice through graduate and post-graduate recruitment to IP licensing. This report therefore touches on a number of areas.

We ask what the effects of state funding of the science base are. This clearly involves a number of questions and hence we confine ourselves to the following. First, science funding is of course channelled through a number of routes, such as QR and research councils. We review how this funding works and its relationship with both the attraction of external funding and a variety of impact pathways including the attraction of overseas R&D. Second, we look at the effect on the UK private sector total factor productivity of publicly funded R&D expenditures using new data across industries and look too at the role of absorptive capacity.

In assessing the impact of the science base on innovation and productivity, it is helpful to bear in mind the systemic nature of innovation and the associated productivity enhancement process. From an innovation system perspective it is important to note as Hughes and Martin (2012) argue that

> "*the impact of publicly funded research will be substantially affected by the capacity of other actors in the economic and innovation system to access, understand and use the research outputs produced with public sector support. This depends to a considerable extent on the R&D that the private sector itself carries out. R&D activity in the private sector has two purposes or 'faces'; it creates new knowledge in itself but it also enhances the firm's 'absorptive capacity' – i.e. the ability of a firm to identify, understand and exploit knowledge developed elsewhere in the innovation system, including in the public sector (Cohen and Levinthal, 1989 and 1990).*"
>
> (Hughes and Martin, 2012, p.12)

The central policy issue, they argue, is therefore not about the relative impact of public versus private sector expenditure. Instead it is the problem of how best to manage the way in which two different types of research active organisations interact. This is the problem of

> "*managing a trade-off between two good things: getting more academic knowledge used by the economy versus maintaining the fundamental missions (long-term research in education) of universities*"
>
> (Foray and Lissoni, 2009, p.13)

In practice the historical evolution of the university sector in the UK has involved multiple and persistent interconnections with the private sector as well as with public sector organisations (Martin, 2012). Moreover, there is extensive evidence to suggest that there are a multiplicity of pathways by which knowledge exchange occurs (Hughes and Kitson, 2012 and 2013).

In this report we therefore provide detailed evidence on the funding of the UK science base from public and other sources along with an analysis of the link between excellence in research and impact related activity and how "third stream" funding of research and knowledge exchange relates to excellence in the science base. We examine, in addition, the evidence relating to a particular class of interactions which may arise when the science base serves as a potential attractor for the location of multinational R&D innovative and productive activities in the UK. Finally, we provide an econometric estimation of the extent to which public sector support of the science base affects total factor productivity in different sectors. It is important to note that this last exercise is not directly concerned with estimating the returns to the economy as a whole over time of changes in the level of support for the science base. That has been explored by one of the current authors elsewhere (Haskel and Wallis, 2013).

We assess the effect of public sector science spending by looking at its relation with private sector "total factor productivity". This latter concept is the following. Productivity is output per unit of input. Single factor productivity, the easiest to measure, is output per single input: for example labour productivity, which is output per hour. Of course, single factor productivity can change if other inputs change. A worker with more capital equipment for example will be more productive, or if the firm copies another firm and finds a better way of organising production output per hour will also rise. Thus "multi factor productivity (MFP)" or "total factor productivity (TFP)" seeks to measure output per range of inputs. The usual implementation is to measure output per labour and capital input. So in the example above, TFP will not rise if a worker has more capital, since that is controlled for. But it will rise if production is re-organised. In this approach, TFP changes when improved ideas increase the output of the combination of labour and capital, so TFP changes are often described as increases in the efficiency of production. So, if for example, a firm benefitted from publicly-financed ideas research that came for free, then TFP would rise. Hence in our study we look for the influence of publicly-financed research on private sector growth in TFP. [1]

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[1] In fact we use a more sophisticated measure of TFP that counts as inputs labour and capital but also ideas that are paid for. To see what happens in this case, note the proviso in the above example that ideas come for free. Suppose instead the complete opposite; that firms paid a licence fee to use all ideas (to patent holders for example) and no ideas come for free. In this case, we should regard the paid inputs to output as being labour, capital and ideas. So to calculate TFP we subtract from output, in addition to capital and labour stocks, the "stock of ideas used" (patents numbers say). When we do this, each input is weighted by the share of its costs in total costs: for ideas, that would be the share of licence fee payments in total costs. In this case, there would be no impact on TFP from paid for ideas, since they are included in TFP already. So completely free ideas will show up as raising TFP: from the public sector for example. Ideas where the market prices completely capture their value in boosting

In estimating cross-industry effects we bear in mind the findings of earlier studies which have primarily focused at the level of the economy as a whole and have typically found substantial rates of return to both private and public sector R&D (Hughes and Martin, 2012). A number of studies have attempted to disentangle the effect of public sector research *per se*. In a study of 15 OECD economies in the period 1980-1998 the responsiveness of public sector research is shown to be positive and higher than the response to private sector research (Guellec and van Pottelsberghe de la Potterie, 2004). This study concludes that the long-run responsiveness or elasticity of total factor productivity to publicly funded research is 0.17 compared to 0.13 for private sector R&D. This is consistent with the view that benefits of private sector R&D are more likely to be captured by the private sector than is the case of publicly funded research which is more concerned with basic fundamental aspects. It is therefore potentially likely to have a wider range of applications, not all of which are captured by the price paid for access to that research by the private sector. Interestingly this study also shows that the responsiveness of total factor productivity to public sector research is higher when business R&D intensity in the economy is higher. This reflects the important complementarity which we discussed earlier. The final interesting finding of this study is that the impact of public sector R&D is higher when the share of university research is higher. This suggests that the impact of public sector laboratory research over this time period and for the economies concerned was less significant than that for university research. One possibility is that government performed R&D may be less likely to have a positive impact economic growth, since it is more concerned with defence issues than is university based research.

A recent study co-authored by one of the current authors of this report which focused on the UK alone also produced results that suggest a positive impact for public sector R&D on total factor productivity (Haskel and Wallis, 2013). They analyse the impact of private and public sector R&D on total factor productivity growth for the UK economy for the period 1988-2007. Their results are similar to those of Guellac and van Pottelsberghe de la Potterie (2004) with similar elasticities for public sector R&D. They find, however, no significant spillover effects on overall economic growth for private sector R&D. They

production will not change TFP, since they are evaluated at their observed market prices. What will change TFP, however, are ideas whose value in boosting production *exceeds* their market price. This would be the case for free ideas, but also for ideas that, even if paid for, but where the inventor was unable to extract all the returns from the use of that idea. Thus a correlation between TFP and publicly or privately funded R&D would be consistent with such "spillovers" of ideas to production, either because publicly funded ideas are free or because privately funded ideas are not priced so that the source where the ideas originate get benefit from them. The strength of this correlation method is that one can interpret the resulting relations in terms of spillovers above and beyond the operation of the market place and so they yield direct evidence upon the types of market and system failures in the connections and communication between business and universities and the knowledge exchange process which form the rationale for policy. The weakness of this method is that it places great demands upon the data including very strong assumptions about what is captured in market prices. For example, suppose firm A does R&D and produces better quality capital equipment. Suppose it then sells it to firm B for a price that completely reflects the gains in productivity for firm B. If the statistical agency correctly measures the improved quality capital equipment, there is no effect on TFP in firm B and so no relation between TFP in firm B and R&D in firm A. However, if the statistical agency does not quality adjust then the measured capital in firm A will be understated and so measured TFP will be high. Furthermore, there will be a relation between R&D in firm A and TFP in firm B, but this is a consequence of mismeasurement of capital inputs and not spillovers.

also find that the effects of public sector R&D are substantially positive for research council funded research, but with no significant impacts for university funding through the funding councils nor for public sector departmental research spending.

There have been a number of other studies which have specifically sought to analyse the complementarity between private and public sector R&D. The most recent of these (Cohen et al., 2002; Jeaumotte and Pain, 2005a and 2005b) conclude that public sector research has a significant positive impact on private sector industrial R&D. In the case of Cohen et al. (2002) which focuses on the US the principal conclusion is that public sector research is critical to industrial R&D in a particular group of industries, and that there are wider effects across US manufacturing. They also find that new business start-ups and larger firms are particularly and positively affected. Jeaumotte and Pain (2005a, 2005b) analyse 20 OECD countries over the period 1982-2001. Their results provide strong support for the complementarity between public sector R&D and business sector R&D. They show that public sector R&D has a positive influence on business R&D intensity at the level of the economy as a whole as well as on patenting activity. As a result of their studies they conclude that

> "*research in the non-business sector is an important component of innovation, both directly, as reflected in patenting, and indirectly through its wider effects on private sector activities. Even though an expansion in public sector research can help to push up wage costs for the business sector, this is more than offset by a positive impact on the labour efficiency of business sector researchers. An increase of 1 standard deviation in the share of non-business R&D in GDP (an increase of 0.06 percentage points for the average economy) raises business sector R&D by over 7% and total patenting by close to 4%.*"
>
> (Jeaumotte and Pain, 2005b, p.38).

Each of these studies requires very strong assumptions to be made in accounting for the contribution of different elements to overall total factor productivity growth. Moreover, they also depend critically on the reality of the time lags taken by which public sector R&D may be expected to impact on total factor productivity. This includes the intermediate stages on the path to the ultimate productivity impact through, for example, the impact of public research on private sector R&D, on patenting and on innovative activities. (For a fuller discussion see Hughes and Martin, 2012).

There is a rich variety of case study and historical narrative material which suggests that time lags between the development of basic scientific research and its findings and implementation in commercialisable products may be very long. In the case of medical research, for example, it has been frequently shown that time lags may be between 15 and 25 years long. This raises the question of whether it is plausible to expect impacts within relatively short time periods from the expenditure on research occurring to productivity impacts. Most econometric time series analyses use time periods of the maximum of up to 6 year lags. For radical breakthroughs and for certain technologies, it seems clear that the time period through commercialisation may indeed span one or two decades. This raises the question of what processes may be at work by which basic scientific research is transformed into productivity growth over shorter periods. In this connection it is important to emphasise once again the multiple pathways through which knowledge exchange occurs. Moreover, in thinking about these pathways it is useful to draw an important distinction between radical innovations which may be transformative in their impact and have very long gestation periods and the more or less continuous process of incremental innovation. Although there is great emphasis in policy debates on disruptive and radical technologies, it remains the case that a very high proportion of productivity enhancing innovation takes the form of gradual and persistent incremental change (Alexy and Salter, 2014). The process by which university research may influence incremental innovation is likely to involve much shorter time periods and be the result of the wide range of interactions which occur along multiple innovation pathways. These include informal advice, problem-solving and consultancy activities and, in particular, through the transmission of knowledge in the form of the recruitment by business of PhDs trained in the research base on projects typically funded by the public sector. To the extent that these pathways transmit knowledge either “costlessly” or at cost below their true value to the businesses concerned, then an increase in public sector research activity may enhance productivity growth over periods shorter than the decades frequently associated with more radical or fundamental transformative breakthroughs.

In this report our focus is not on the impact over time of public sector research on total factor productivity growth, but rather on the extent to which that impact varies across different sectors. Moreover, we locate the econometric analysis of total factor productivity growth across sectors in the context of a detailed discussion of transition pathways. In addition, we explicitly allow for the complementarity between public and private sector R&D by including the effects of both in our analysis of total factor productivity change. We also explicitly model the impact of the interaction between private and public sector R&D. Finally, in addition to looking at the moderating influence of private sector R&D on the impact of public sector R&D, we also explicitly attempt to model the impact of closer interaction pathway activities between the private and public sectors. We do this by assessing the extent to which the impact of public sector R&D on sector level total factor productivity change is moderated by the extent of co-operative activities between firms in different sectors and the science base.

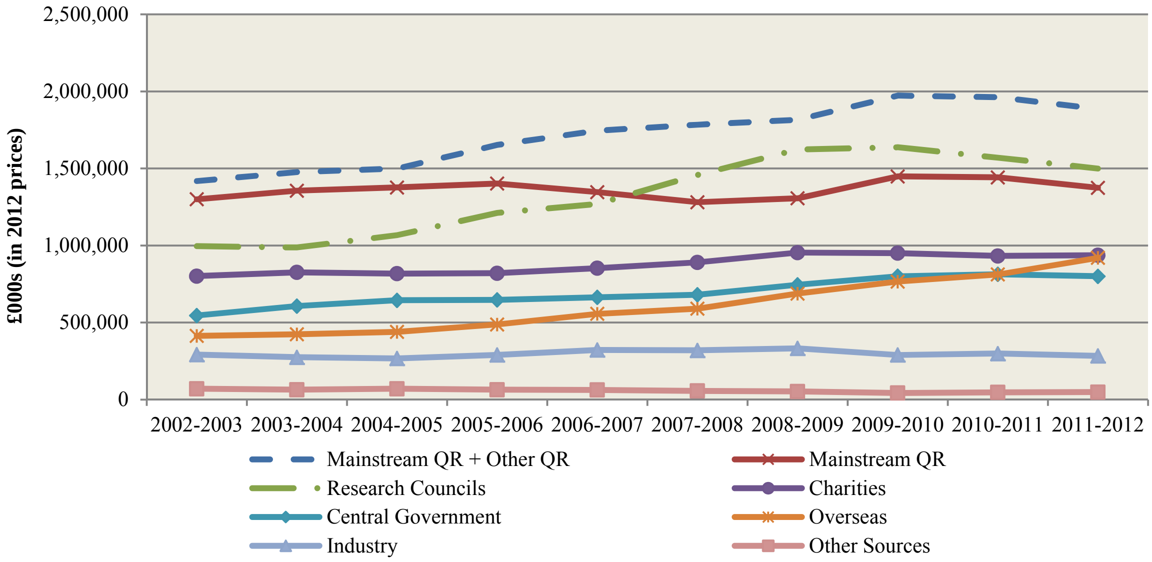
2 Public Funding for University Research

Public funding for research in the university sector in the UK is provided through two main routes. The first is provided through the Funding Councils for England, Scotland and Wales and the Department for Employment and Learning in Northern Ireland. This so-called mainstream quality related (QR) funding is based upon periodic backward looking research assessment exercises. The Funding Councils also allocate further sums based on the attraction of business or charity funding and the scale of PhD training provision. The second element of public funding is allocated through the research councils which cover the whole of the UK university sector. The research council element is in principle an essentially forward looking exercise since funding is based on proposed research activities.

In addition to funding through these two routes individual universities may receive funding for research from a variety of other sources. These may be grouped by source into charities; central government; industry; overseas funders, including EU sources; and other sources.

Exhibit 2 shows that there has been an increase in real terms in the last decade in both QR and research council funding.

Exhibit 2 The Funding of UK University Research: Dual Support and Other Sources 2002-3 to 2011-12 (in 2012 prices): All Disciplines



Funding from overseas has also increased substantially over this period. Slower increases have taken place in charitable and central government funding whilst there has been, if anything, a slight decline in funding from industry. In terms of public funding, the most notable change is the acceleration in research council funding in the middle of the period. However, this reflects to a substantial degree the increase in such funding consequent to the introduction of full economic costing of research grants. This was introduced on the basis that the research being carried out would be properly funded with a full contribution to overhead costs and that it would not be accompanied by an increase in the amount of the research conducted *per se*. [2] At the same time there was a switch in the balance of quality related funding so that mainstream QR over the period increased more slowly than total QR which as the period progressed included both substantial increases in funding associated with PhD training programmes and in the later years was augmented by funding to cover the overhead costs associated with obtaining charitable funding and also an element of funding to act as an incentive to support industrial funding. The result of these trends is that the balance of quality related and research council funding has shifted towards the research councils while the introduction of non-mainstream QR has maintained the overall higher proportion of total QR in the dual funding stream. All of the series for public funding show a fall in real terms after 2008-9.

3 Impacts of Research Funding

3.1 The Science Base and the Location of Multinationals' R&D

In this section, we present a brief survey of the literature on the R&D investment location decisions of multinationals, with a particular focus on the role of the science base in the UK.[3] The location of R&D activities is the outcome of a very complex and costly decision-making process, involving a number of both financial and non-financial factors and depending on the relative levels of economic and technological development of both home and host countries. Such factors might include the size of the local market, cost levels, the quality of local institutions, labour and intellectual property regulations, availability of skilled workforce and some level of technological and scientific expertise among these factors.

We will first examine briefly the literature on the overall location decision of (multinational) firms. Then, we will examine the particular case of the R&D location decision.

There is a large and diverse literature on the factors driving the location decisions of multinational firms (MNEs) (Iammarino and McCann (2013) and Cantwell (2009)). Within this literature an important

[2] See for example Alexander 2009 and Wakeham 2010.
[3] We do not review the extensive literature documenting the general nature of university-industry links and the benefits of the co-locations of firms and universities *within* countries except to note that there is substantial evidence of a positive correlation (e.g. Anselin et al. (1997), Harhoff (1999), Helmers and Rogers (2010).

contribution to understanding the MNEs' internationalisation process is Dunning's eclectic (OLI) paradigm. Dunning (2000) proposes three groups of variables to explain MNE's location choice. These are: ownership specific advantages (O), location specific advantages (L), and internalization specific advantages (I). Amongst the ownership advantages, Dunning distinguishes between asset advantages and transaction cost minimizing advantages. Asset advantages are firm-specific ownership advantages generated by some particular intangible assets such as multinational experience, experience of a specific technology, or the type of R&D project. This latter aspect of the OLI Paradigm may explain the internationalisation of R&D, as the ownership-specific competence of a multinational firm can be complemented or augmented by assets created by R&D realised in a foreign location (Demirbag & Glaister, 2010; Blanc & Sierra, 1999; Dunning, 1977). Foreign firms either enter the domestic market to exploit their comparative advantage in the host country, or for locational advantages, to access technology that is generated by host country firms, known as "technology sourcing". In the latter case, foreign firms are motivated by the possibility of connecting with local innovation systems (Guinet & Backer, 2008). Recent literature on the internationalisation of R&D (Florida, 1995; Guinet & Backer, 2008; von Zedtwitz & Gassmann, 2002) also highlights access to a strong knowledge-base as a factor driving foreign investment in the R&D sector.

Taking into account the type and the motivation of inward Foreign Direct Investment (FDI) is particularly important when one evaluates the productivity impact on the host country. In case of technology sourcing FDI, the extent of productivity gains for the host country may be limited, or may even occur in the other direction, i.e. from domestic to foreign enterprises (Driffield & Love, 2005). This type of FDI is more likely to take place in industrialised countries (van Pottelsberghe de la Potterie and Lichtenberg, 2001).

In the case of the UK, Driffield and Love (2005) show that the overseas owned sector of UK manufacturing benefits from productivity spillovers in knowledge-intensive industries, both from UK-owned firms and other foreign-owned firms. Driffield and Love (2007) explore in detail the motivation for foreign FDI in the UK, and identify four types of FDI; technology sourcing/location advantages; technology sourcing, efficiency sourcing and ownership advantage. Domestic firms only gain from FDI motivated by ownership advantages; technology-sourcing inward FDI does not lead to productivity spillovers to domestic firms (Driffield & Love, 2007). This perverse effect of technology sourcing FDI is corroborated by the findings for the engineering sector (Girma & Görg, 2003, 2007).

However, firms are increasingly locating their R&D facilities outside their home countries (Hall, 2011) and this increasing internationalisation of R&D may have different effects on the host country, than does foreign direct investments *per se*.

Regarding the motivations for (re)locating R&D activities, Thursby and Thursby (2006) have reported that for more than 75% of US firms, expansion was the main reason for an R&D investment in a new area. Recent evidence shows that the pattern and nature of internationalisation of R&D has been shifting from developed Western countries to low-cost regions (Atkinson, 2007; Lewin et al., 2009). In the case of relocating R&D to less developed countries, MNEs are primarily aiming to adapt their technology to local conditions and complement their production and sales activities in the host countries. They are pursuing, therefore, a technology exploitation strategy (Hakanson & Nobel, 1993; Odagiri & Yasuda, 1996). The level of the intellectual property rights' protection in the host countries has also been found as an important positive encouraging inward investment factor (Ito & Wakasugi, 2007).

Locating R&D units in relatively developed countries is more driven by a technology exploration or a technology augmenting strategy (Thomson, 2013). Of course the same factors listed for developing countries, related for example to market size will matter for investing in more developed countries, however they will be accompanied with factors related to the scale and quality of the knowledge base. In this context, the quality and specialisation of universities, research institutions and scientists have been shown to be of central importance (Pearce, 1999; Pearce & Papanastassiou, 1999; Thomson, 2013).

From an empirical point of view, we can distinguish between three main analytical approaches to investigate the determinants of the location of R&D activities (Rilla & Squicciarini, 2011). The first group of studies mainly uses surveys to evaluate the drivers and motivations for locating R&D activities abroad (Kuemmerle, 1999); the scope, activity, type and performance of the foreign R&D units (Florida, 1997); and the organizational and operational aspects of foreign R&D (Gassmann & von Zedtwitz, 1999; von Zedtwitz, Gassmann, & Boutellier, 2004). The second group of contributions is mainly based on quantitative studies using R&D investment, patents and other innovation-related data (Le Bas & Sierra, 2002; Patel & Vega, 1999; Thomson, 2013). This strand of analyses focuses on the relative resource endowments and technological advantages of the home and host countries. Finally, there is a group of qualitative and quantitative studies that investigates the knowledge flows to and from foreign R&D units, such as patent citation analyses (Almeida, 1996; Jaffe et al., 1993)

In relation to the role of scientific capacity of a country in attracting inward R&D, Thomson (2013) shows that scientific capacity is a key factor in attracting such 'offshoring' of R&D and that it also affects the likelihood that a country's firms also make 'offshoring' R&D. On average, however, he also shows that firms source technology from less technologically advanced countries. This would imply a strategy of accessing 'niche' knowledge or skills and at the same time that the countries with the highest level of university based scientific capacity will have both high inward and outward flows of R&D investors (Thompson, 2013).

The UK has the highest share (around 20%) of externally funded R&D amongst the major industrial economies and is an extreme outlier in this respect (Hughes and Mina, 2012). It is also an economy with an exceptionally high overseas ownership of businesses carrying out R&D.

It is important to understand the role of the public sector science base in this pattern. Pearce and Papanastassiou (1999) show that the desire to 'make effective use of a strong UK technological capability in areas of science particularly relevant to our industry' is a significant factor in the decision of MNE locating R&D facilities in the UK. The authors report that of their respondents in the sample of 48 responding labs 4% considered it the only relevant influence, 52% a major one, 24% a minor one and only 20% rated it as irrelevant (Pearce & Papanastassiou, 1999, p.36). This suggests a strong positive 'pull' role for public sector funding of the science base.

Abramovsky et al. (2007) provide an econometric analysis of the relationship between universities and the location of R&D activities. They use data from the UK Research Assessment Exercise (RAE) to distinguish between research departments that perform world-class research and others. They find that foreign-owned R&D labs in the pharmaceuticals industry are particularly likely to locate in the same area as high quality research chemistry departments. This effect holds, controlling for the presence of science parks and a high-skilled workforce. They find much weaker co-location effects in other industries such as machinery and communication equipment.

In a follow-up study, Abramovsky and Simpson (2011) use continuous spatial measures to assess the role of physical distance in industry-university interactions. They also look at whether survey-based measures of university co-operation are larger in firms located close to universities with particular departments e.g. chemistry, or materials science. Once again, pharmaceutical firms are found to locate their R&D near (within 10 km) to world-class rated chemistry departments. As in their previous study, the location decision seems to be also related to the presence of science parks. For the chemical industry, although the distance between R&D labs and university materials science departments is longer (around 80km) compared to the pharmaceutical sector, geographically closer firms tend to interact more with universities. On the other hand, the authors find less evidence in other industries of firms making their location decision because of proximity to university departments. For example, in the case of vehicles and machinery industries, the location of R&D activities seems to follow production linked disciplines such as materials science, rather than research departments. In electrical machinery, TV and radio equipment, aerospace and precision instruments, they find no econometric evidence linking the location of R&D activities to university research.

The general evidence of the international location of R&D suggests that the UK's outstanding university sector should be a strong attractor for overseas funding of R&D in the private sector and the location of

R&D activity in the UK. There is support for this proposition on both qualitative and quantitative grounds. On this basis public sector funding "crowds in" private sector R&D from abroad.

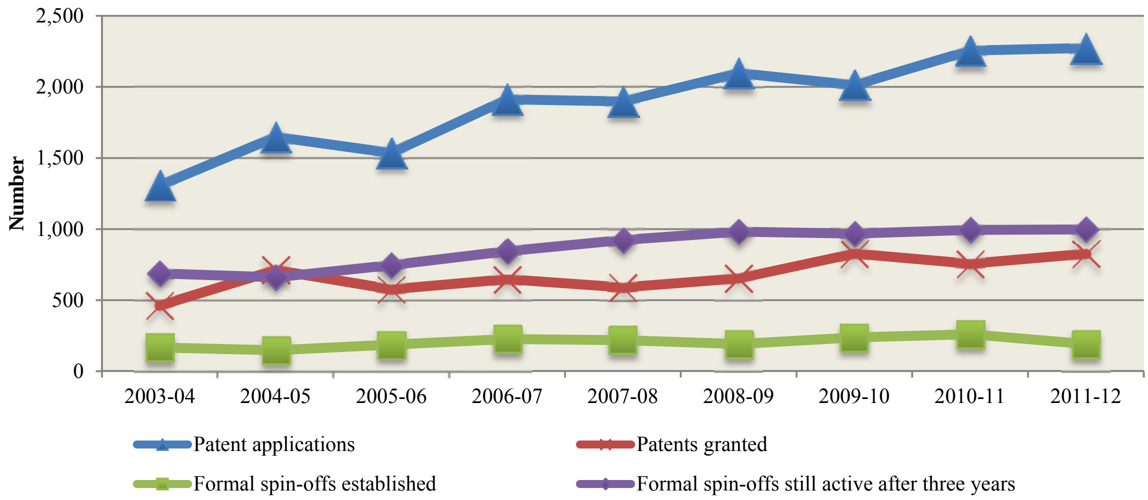
3.2 Public Sector Funding and Private Sector willingness to pay for Access to Knowledge

In terms of the potential impact of the public sector funding flows, it is useful to look at the way in which university research funding relates to trends in External Income Generation (sometimes called Third Stream Income). This might be considered an indicator of willingness of the private sector to pay for potential outputs derived from research carried out in the science base. Data on trends on this External Income Generation are available from the Higher Education Business Community Interaction Survey (HEBCIS).

The HEBCIS data provides evidence on a number of different sources of external income generation.

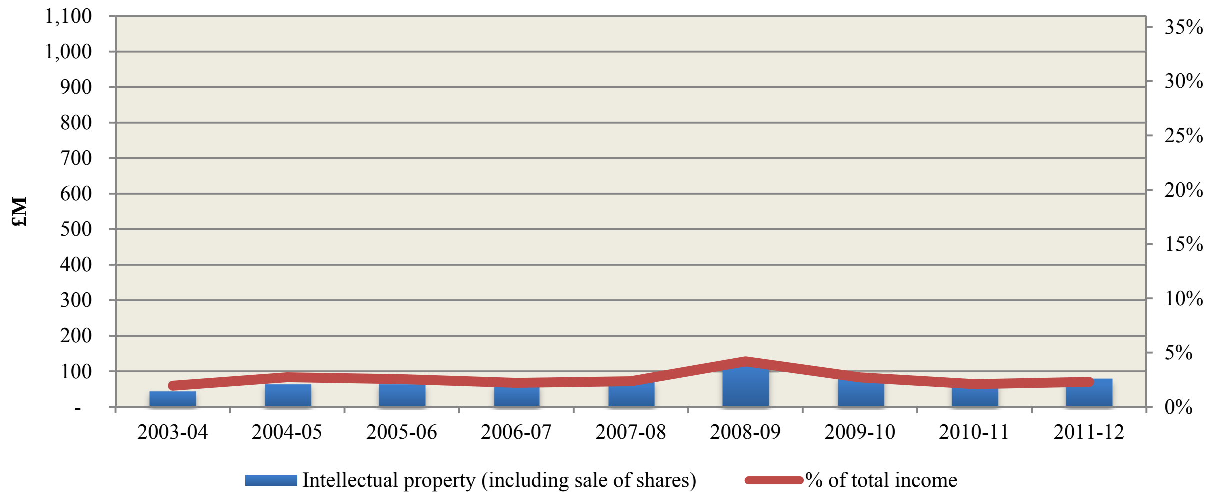
Exhibit 3 provides evidence related to university spin-off and patenting activity over the period from 2003/4 to 2011/12. This shows a steady increase in the number of patent applications over the period and a somewhat lower rate of increase of patents granted. Formal spin-offs established show little trend whilst there is a slow upward increase in the number of formal spin-offs that are still active after three years which might be regarded as a more useful quality related measure of spin-off activity.

Exhibit 3 University Spin-off and Patenting Activity 2003-2011



A further indication of commercialisation activity is related to income from intellectual property, such as patenting and licensing, and also the sale of shares. This is shown in Exhibit 4 and has been at a relatively low level throughout the period and peaked in 2008/9. As might be expected, in the aftermath of the financial crisis this has fallen back to levels experienced at the beginning of the decade.

Exhibit 4 Intellectual Property (including Sale of Shares)



Collaborative research and contract research are shown in Exhibits 5 and 6 respectively and have both increased in real terms over the period. The latter has also increased as a share of overall third stream income.

Exhibit 5 Collaborative Research

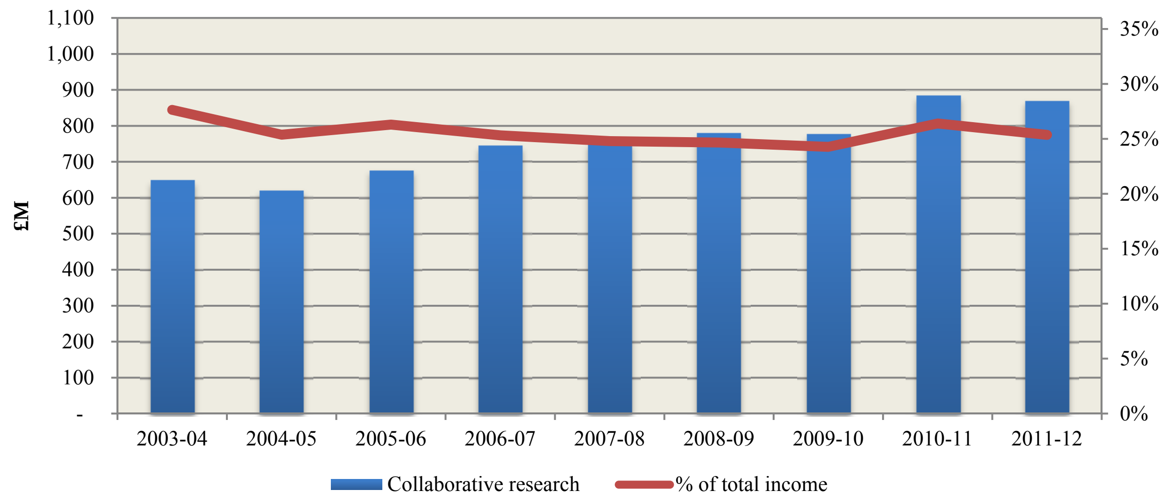
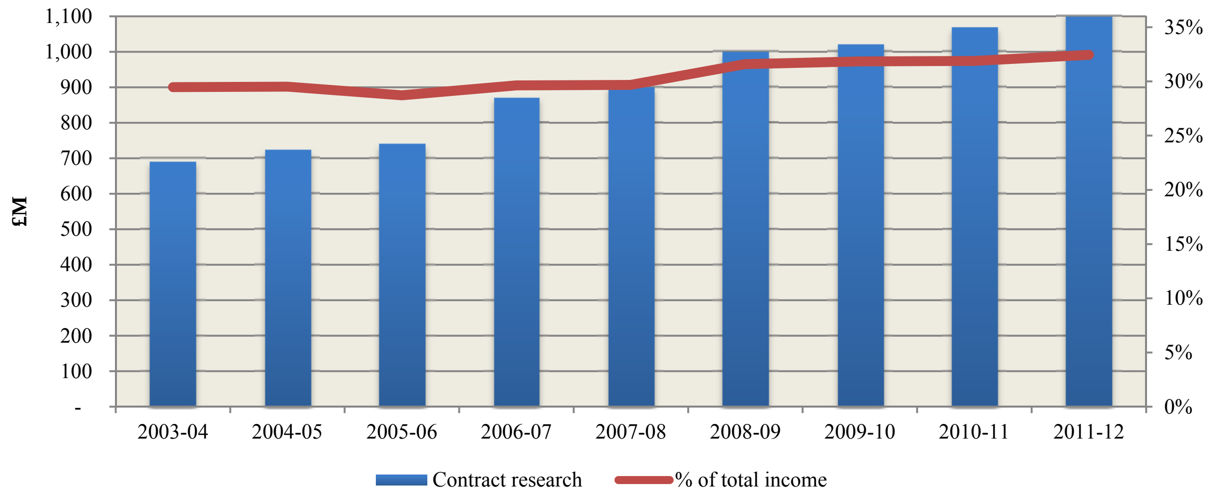


Exhibit 6 Contract Research



Consultancy income shown in Exhibit 7 starts from a lower base and has increased very moderately. A similar slow increase is exhibited in income from continuing professional development and continuing education (Exhibit 8).

Exhibit 7 Consultancy

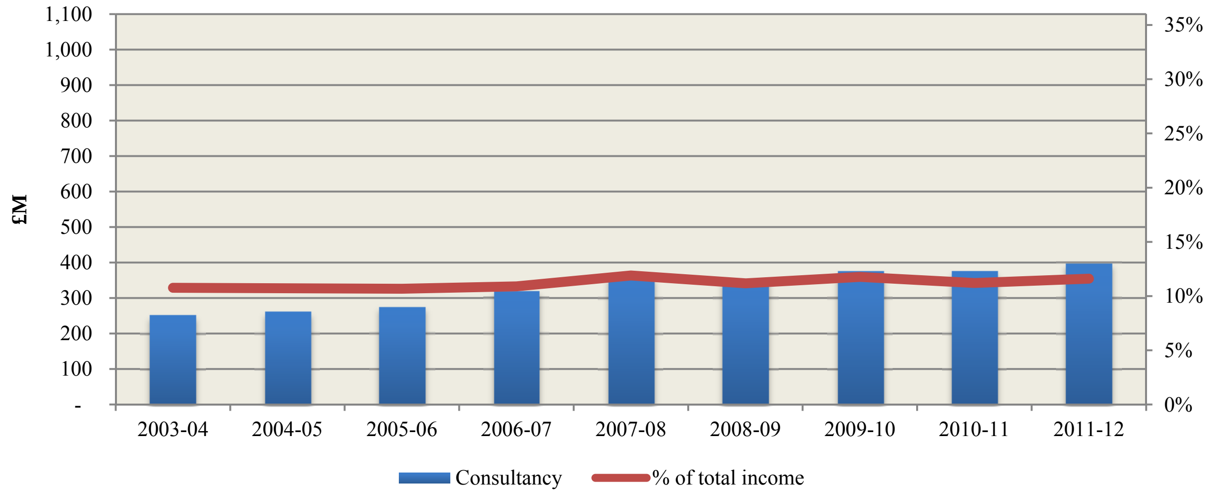
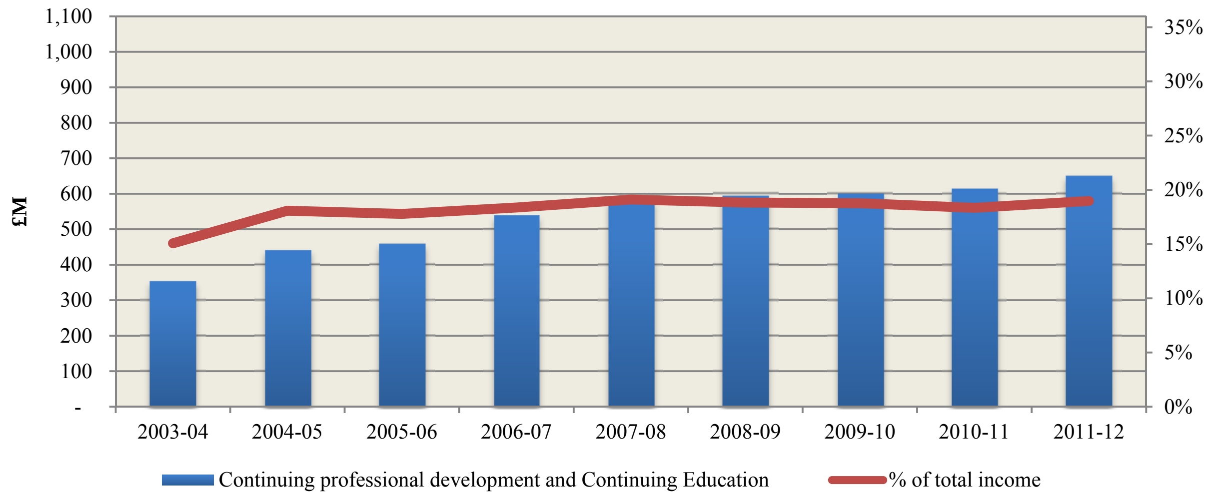


Exhibit 8 Continuing Professional Development and Continuing Education



Regeneration and development programmes shown in Exhibit 9 have declined whilst income from facilities and equipment related services (Exhibit 10) have been relatively stable.

Exhibit 9 Regeneration and Development Programmes

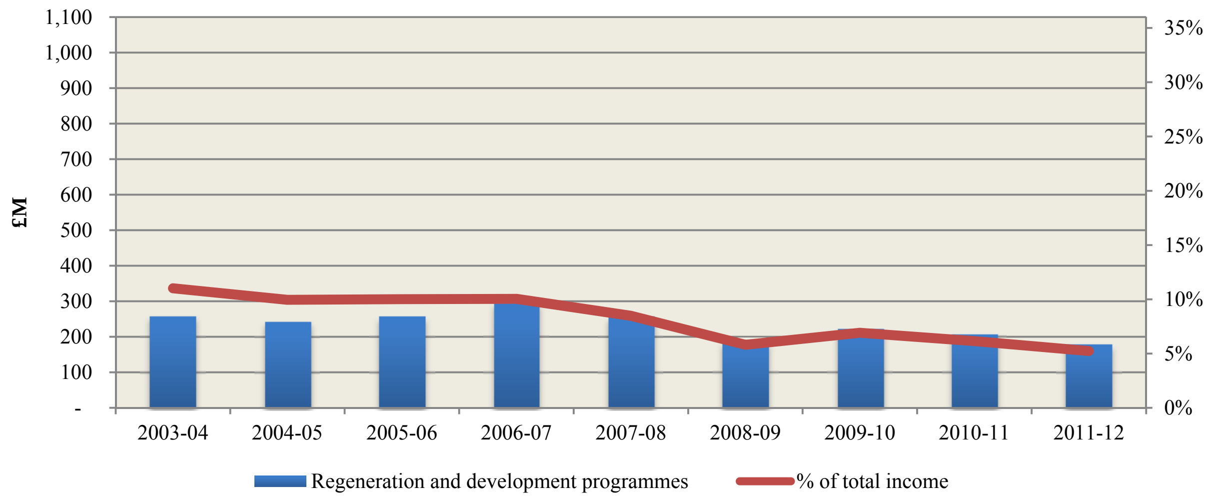
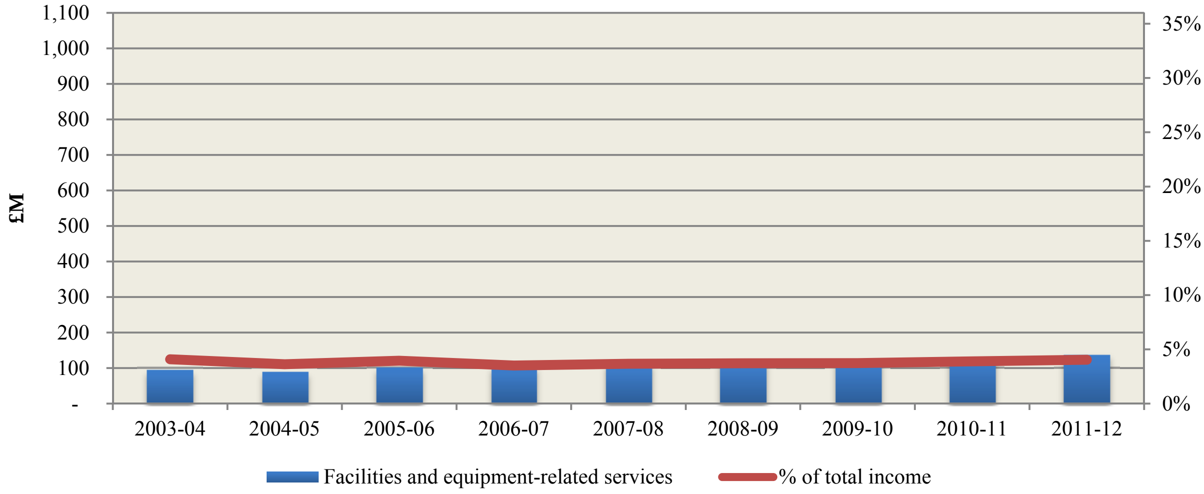


Exhibit 10 Facilities and Equipment-Related Services



Taken as a whole, External Income Generation has in general been rising alongside public funding. From an impact perspective it is therefore interesting to ask whether research funding is related to external income generation at the university level. One way of doing this is to see if universities which account for the bulk of activity also account for Third Stream Income Generation. Exhibit 11 therefore looks at the share of external income accounted for by universities ranked in the top 10% in terms of research funding.

Exhibit 11 External Income Generation and Share in Total Research Funding of the Leading 10% of Universities ranked in terms of Total Research Funding 2011-12

	All Universities Total External Income £m	Share of Top 10% Universities by Research Funding in External Income Generation %
Collaborative Research	871	48.2
Consultancy	399	37.2
Contract Research	1,114	62.6
Intellectual Property	79	59.5
Facilities & Equipment	139	34.8
Regeneration & Development	180	18.6
Continuing Professional Development	651	24.3
Total External Income	3,432	
Share of Top 10% of Universities in Total External Income	45.2	
Share of Top 10% of Universities in Total Research Funding		62.5

Note: Share in Research funding is defined as share in total research funding from all sources shown in Exhibit 2 (QR, RC, Charities, Industry, Central Government, Overseas and Other Sources).

The bottom row shows that the top 10% of universities in terms of research funding accounted for 62.5% of all such research funding in the UK. The penultimate row shows that these same universities accounted for 45.2% of all external income generated by the UK university sector. It is clear that research funding is highly concentrated in relatively few universities and although the same is true for external income, the concentration is somewhat lower.

It is noticeable, however, that the concentration of external income generation is highest in terms of contract research, collaborative research and intellectual property. The involvement of the top ranked research universities in the generation of third stream income is much lower in relation to local regeneration and development activity and also in relation to continuing professional development. This pattern is also reflected in assessments of individual academic pathways to impact. These were examined in a recent major survey for the UK which indicated that academics in the Russell Group universities were more likely to be relatively focused on national and international and research related activities than the post-1992 group of universities, whilst the latter tended to be more embedded in their local and regional economies and relatively more concerned with labour market skills and professional development activities (Hughes and Kitson, 2013). This suggests an appropriate element of specialisation and differentiation within the university system in the UK. Many universities with relatively low levels of QR or RC funding may specialise in and attract substantial external income related to non-research intensive activities.

Exhibit 12 The Relationship between the Generation of External Income in the Period 2008-12 and Public Research Funding in UK Universities 2003-2007

Model 1.1: $\log\left(\frac{TEI}{FTE}\right)_t = \alpha + \beta_1 \log\left(\frac{TEI}{FTE}\right)_{t-1} + \beta_2 \log\left(\frac{TQR}{FTE}\right)_{t-1}$

Model 1.2: $\log\left(\frac{TEI}{FTE}\right)_t = \alpha + \beta_1 \log\left(\frac{TEI}{FTE}\right)_{t-1} + \beta_2 \log\left(\frac{RC}{FTE}\right)_{t-1}$

Model 1.3: $\log\left(\frac{TEI}{FTE}\right)_t = \alpha + \beta_1 \log\left(\frac{TEI}{FTE}\right)_{t-1} + \beta_2 \log\left(\frac{TQR+RC}{FTE}\right)_{t-1}$

	Model 1.1	**Model 1.2**	**Model 1.3**
(Intercept)	0.967*** (0.123)	1.119*** (0.128)	0.940*** (0.118)
$\log(TEI/FTE)_{t-1}$	0.653*** (0.048)	0.607*** (0.049)	0.632*** (0.048)
$\log(TQR/FTE)_{t-1}$	0.079*** (0.022)		
$\log(RC/FTE)_{t-1}$		0.110*** (0.024)	
$\log((TQR+RC)/FTE)_{t-1}$			0.103*** (0.024)
R-squared	0.689	0.708	0.701
Observations	137	137	137

Data: HESA and HEBCIS

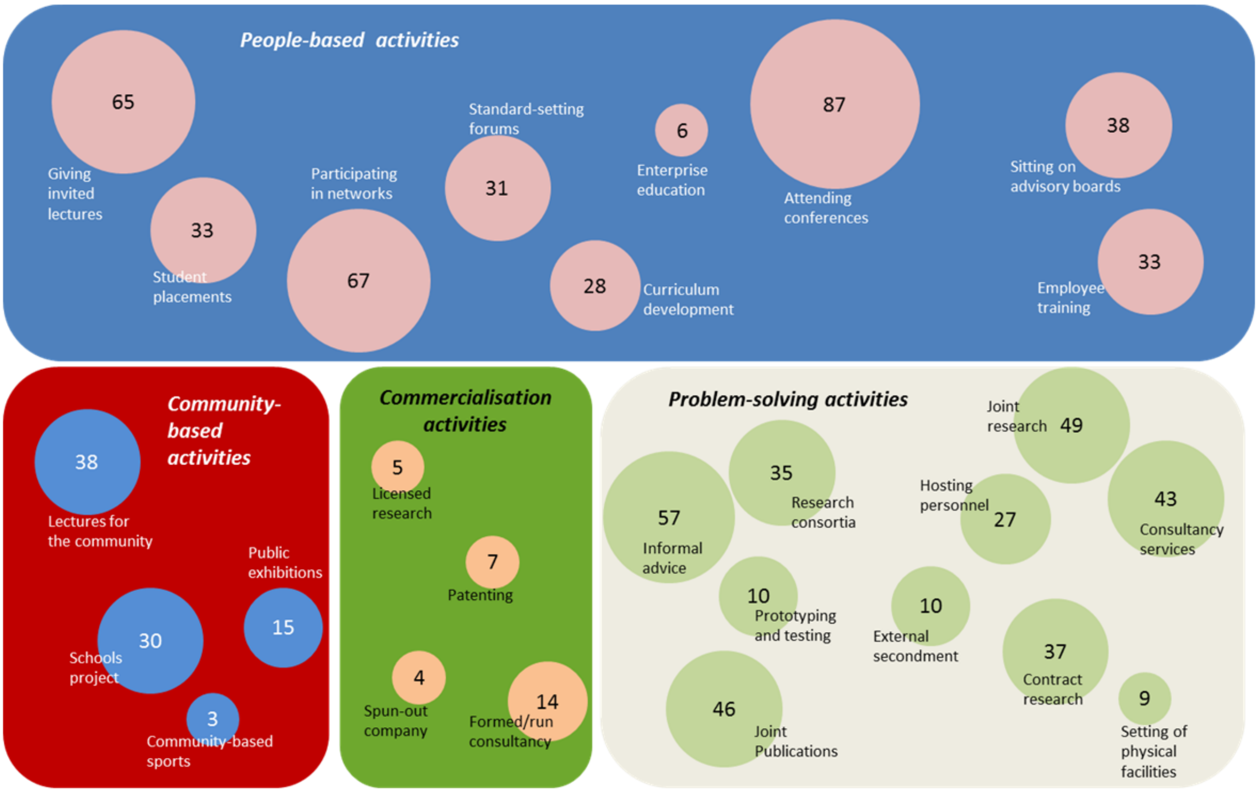
Notes:
*** significant at the 1% level
TEI Total External Income
TQR Total QR (mainstream QR plus charitable, industrial and doctoral elements)
RC Research Council Funding
FTE Full time equivalent staff
t-1 2003-7
t 2008-12

The relationship between public sector research funding and external income generation is explored further in Exhibit 12. This shows the results of a regression analysis relating total external income generated in the period 2008-12 to respectively Total QR funding, RC funding and both combined in the period 2003-07. The relationship is lagged to reflect the time it takes to translate research activity into a potential attractor for external funding. Because we expect some persistence in the generation of the external income generation over time, we also include as an explanatory variable external income generated in the previous period. Since as we have shown above that the distribution of research income and external income is extremely skewed, we analyse the data using a logarithmic transformation. There is a strong positive correlation between the attraction of external income and the receipt of QR funding as well as the receipt of RC funding separately and of the two sources combined. It therefore appears that, in terms of "willingness to pay", public research funding leverages complementary funding from private and other sources.

3.3 Public Sector Funding and Pathways to Impact

So far the emphasis has been upon income generation using data at university level. We can also examine pathways to such relationships by analysing data on the behaviour of individual academics. This includes many impact pathways in addition to those based on income generation. This is shown in Exhibit 13 which we have grouped into people-based, problem-solving, commercialisation and community-based activities. Very high levels of activity across multiple pathways are shown. It is important to note that commercialisation pathways *per se* are a relatively small part of the picture. People flows in particular are an impact pathway highly valued by the private sector. There is substantial evidence to support the impact of PhD training as reflected in salary premia, and student placements as, for example, captured in evaluations of the Knowledge Transfer Partnership Scheme linking university postgraduates to small companies (for a full discussion see Hughes and Martin, 2012).

Exhibit 13 Impact Pathways of UK Academics: All Subjects (% reporting having taken part in a pathway activity in past 3 years)



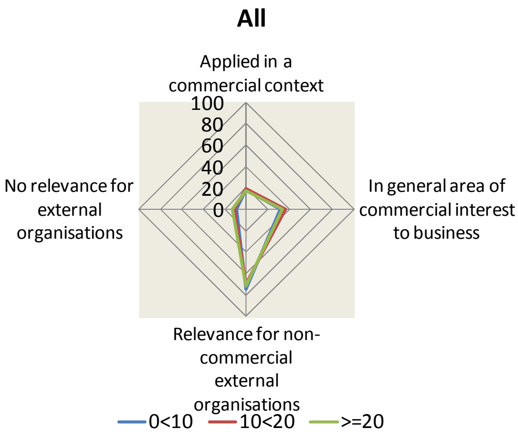
Source: Hughes et al., 2013

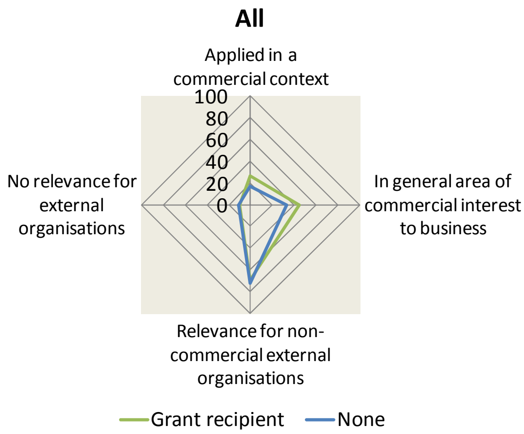
It is possible to examine the extent to which involvement in these pathways is related to either the receipt of a research council grant or being located in a department which received a high quality rating (and hence high QR) in the 2007 RAE. [4]

Thus in Exhibit 14 it appears that recipients of research council grants are more likely than non-grant holders to have research applied in a commercial context and for that research to be in a general area of commercial interest.

[4] For the full analysis of the relationship between QR Research Council Funding and Impact Pathways see Hughes et al. (2013).

Exhibit 14 'If undertaking Research, which of the following statements apply?' Science Academics by RAE score of the Department and Grant Holding Status



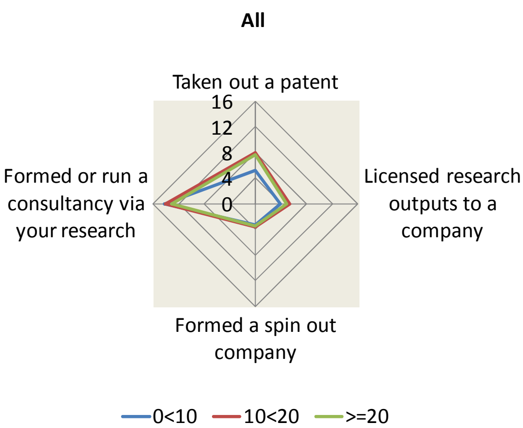


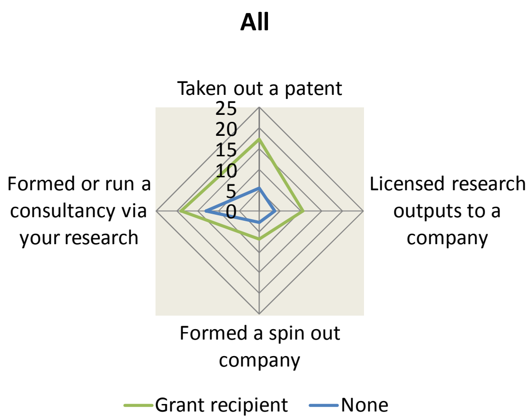
% of Publication Rated 4* in 2007 RAE

Source: Hughes et al., 2013

Similarly, Exhibit 15 shows that grant holders are much more likely to have taken out a patent, licensed research outputs, formed a spin-out company or started a consultancy than non-grant holders. Differences related to whether or not the academic is in a department with a high proportion of outputs rated 4* in the 2007 RAE are less clear cut.

Exhibit 15 Whether Academic Scientists participated in patenting licensing spin outs or consultancy in the last three years by RAE score and Grant Holding Status



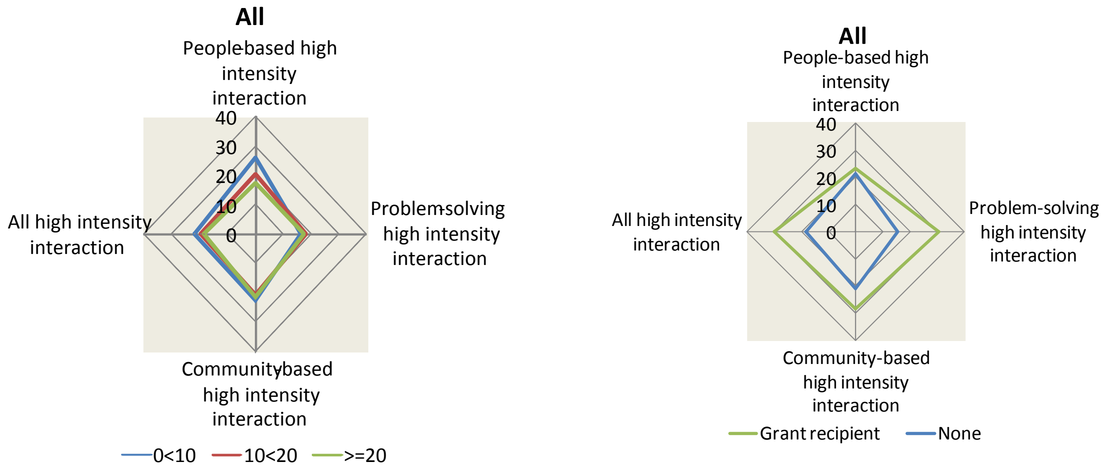


% of Publication Rated 4* in 2007 RAE

Source: Hughes et al., 2013

Exhibit 16 provides a summary overview of pathways activities grouped into high intensity people-based, problem-solving, community-based and all pathways. This uses the grouping of pathways shown in exhibit 13. An academic is classed as a high intensity interactor, if they have taken part in a majority of pathways in a particular grouping. Research council grant holding is positively associated with all four groupings of intensive interactions.

Exhibit 16 Highly connected Science Academics by RAE score and Grant Holding Status



% of Publication Rated 4* in 2007 RAE

Source: Hughes et al., 2013

Taken together this evidence suggests that there is a strong set of actual and potential linkages between publicly funded university research and the private sector and that holding a research council grant is associated with higher levels of such activity. In the next section we examine whether we can identify links at a broad industrial level between RC funding and the productivity performance of businesses. This complements the analysis in this section which has focused on potential pathways to such impact.

4 The Impact of Public Sector Science Base Funding on cross-industry Patterns of UK Total Factor Productivity: Model and data

4.1 Model outline

In this section of the report we analyse the relationship between total factor productivity and public sector science funding in the UK in the period 1995-2007. This is complementary to previous work by one of the current authors which analysed effects for the economy as a whole over a longer period (Haskel and Wallis, 2013). In this study we use industry data and build on the insights of the nature of university-industry links discussed in the previous sections.

The work in this report takes the broad form

$$\Delta \ln TFP_{it} = \alpha_{it}\left(\Delta \ln R_{it}^{PRIV}\right) + \beta_{it}\left(\mathbf{M}\Delta \ln R_{\_i,t}^{PRIV}\right) + \gamma_{it}(\mathbf{P}\Delta \ln R_{t}^{PUB}) + v_{it} \qquad (1)$$

This equation says that ΔlnTFP in industry i depends upon three changes in "usable" or "useful" knowledge stocks denoted by the three terms in brackets on the right hand side of (1): private sector within industry i, private sector outside industry i, and public sector. Outside usable knowledge stocks consist of changes in the knowledge stock, denoted ΔlnR, times the extent to which such changes contributes to the usable stock of outside knowledge relevant to industry i, captured by M and P. That is to say, M and P "scale" the outside knowledge stock to that which is potentially relevant and appropriable by the industry (so for example, if most outside knowledge stock changes are driven by new knowledge in materials science, this may have little relevance for the contract cleaning industry and hence a scaling factor for that industry would be desirable to capture this). The final terms counts any other unmeasured effects. (As a matter of notation, we denote a knowledge stock in this paper by R and the corresponding nominal investment flow in new knowledge, that is to say nominal R&D spend, by $P^N N$. We use "PRIV" and "PUB" to denote private and public spend. Industries are UK market-sector industries; we have insufficient data on public sector output to include them and we exclude the real-estate industry and its capital from our data).

As well as the scaled knowledge stocks in (1) we have also to measure the coefficients in (1), which are, here the elasticity of TFP growth with respect to ΔlnR. Cohen and Levinthal (1989) contain a careful description of what factors affect the ability of firms to absorb the "useful" knowledge stock (to a certain extent, converting the outside knowledge stock into what is "useful" might measure this).

As is well-known, CL suggest that absorptive capacity might depend on own-firm R&D spend ($P^N N$ in our notation). We have in addition, survey information on whether firms co-operate with universities or public research organisations and whether they get their information from them. We regard this as a measure of absorptive capacity, or at least as a summary of whether firms are interacting with universities. In addition, we know if the firm undertakes R&D as well as co-operating (see also Harris and Li, 2008 and Harris et al., 2013).

Our broad strategy below is then to experiment with a number of variables that might pick up P and γ. At this level of aggregation, we note that it will be difficult to distinguish between them.

4.2 Data on co-operation

The micro data on co-operation comes from the UK Wave of the Community Innovation Survey (UKIS), and has information on the UK firms' innovation activities, R&D investments and interactions between UK firms and universities, higher education institutes or government research organisations. In this section we will briefly present some descriptive statistics and discuss the construction of empirical measures.

Conducted by BIS, the Community Innovation Survey provides a regular snapshot of innovation inputs and outputs and presents the basis for comparisons with other European countries. The survey includes information on firms' innovative activities and investments, sections on factors that hamper innovation, the impact of innovation on the business and the sources of information used. It also touches on aspects of the wider innovation process, such as the introduction of new management techniques. The Community Innovation Survey (CIS) was originally conducted every four years, but since 2005 has been conducted every two. The UK wave of the survey is voluntary, and is conducted through both a postal questionnaire and telephone interview for businesses that hadn't yet completed a postal response. In this project, we have used 4 waves of UKIS; UKIS3 covering 1998-2000, UKIS4, covering 2002-2004, UKIS 5 covering 2005-2007 and UKIS6, covering 2006-2008.

With regard to the terms in equation 1, the CIS questionnaire allows us to compile a number of different P matrices in a number of dimensions (in this report we focus on the P matrix and not on the M matrix). First, firms are asked if they have formal co-operation agreements with universities or government research centres. Second, they are also asked if they find information from universities or government research centres a source of innovation (they are asked to rate this as important on a 0, 1, 2, 3 Likert scale (not important, low, medium and high importance). We can construct measures of the fraction of firms in the industry with

a. formal agreements
b. those who find universities/government research labs information of any importance to innovation (i.e. 1, 2 or 3)
c. same as b, but just of medium or high (2 or 3)
d. same as b but just high (3)

Third, we can also measure whether firms do any outside co-operation at all.[5] Fourth, we can then construct these measures but for subcategories of firms e.g. co-operation fractions for firms who spend on R&D.

In constructing these measures we seek the fraction of firms in the industry for the particular measure.[6] With access to the micro data, we can construct measures for each wave of CIS that vary by industry and time. Some of the industries are, however, quite small and as a result data are missing in some years. As a first pass then, we constructed an industry panel by averaging over the CIS waves. As it turns out, many of these measures are heavily correlated. For example, the fraction of firms co-operating with universities is very highly correlated with the fraction co-operating with government research centres. Likewise, the fractions reporting these institutions as useful sources of information are very highly correlated. In addition, there is very high correlation across these measures for subgroups e.g. the fraction of co-operating with universities and the fraction of R&D performers co-operating with universities. What is less well correlated is the fraction of firms who co-operate in any dimension with these measures. Thus we lose little information by only considering two measures

(a) the fraction of all firms in the industry co-operating on any dimension
(b) the fraction of all firms in the industry co-operating with universities or government research institutions

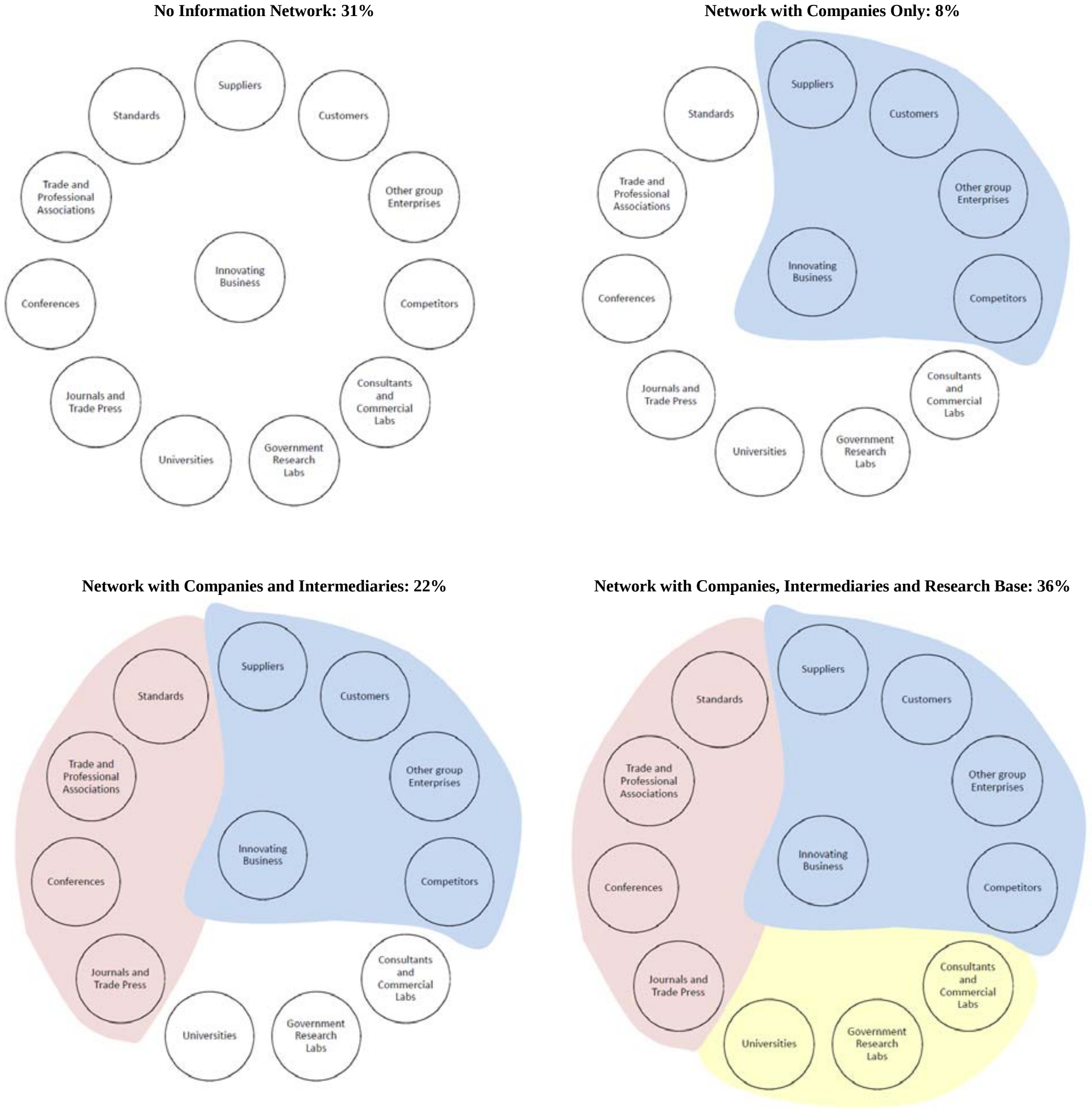
and we can look at these measures according to whether, in addition, firms are currently spending on R&D. Firms in the micro data are also asked if they are spending on broader intangible assets, although this is poorly reported.

[5] The interpretation here is potentially quite complicated. Suppose firm A co-operates with the public sector and firm B does not. But suppose now that firm A co-operates with firm B in the same industry. Thus industry TFP rises following a rise in science spend via the direct link to firm A but also the indirect link to B. We would only capture the direct link if we interacted science spend with COOP (public). We capture the indirect link if we interact science spend with COOP (any). Strictly speaking in this example one might interact COOP with the industry R&D spend, since such co-operation might also include co-operation with suppliers if the industry boundary includes both up and downstream firms as it likely does. Interacting with outside industry spend is not possible since we don't know which industries firms co-operate with. We may, therefore, think of COOP (any) testing the sum of direct and indirect effects.

[6] Weights are available in the micro data for each firm, but at the time of writing it is not clear just what these weights correspond to. Sampling on the CIS is stratified by employment size, industry and area. There is an additional response bias weighting issue in that by no means all firms respond to all the questions. We are not aware of any weights for response bias. Data is published at industry level for some of these measures, which are weighted. We have therefore constructed alternative measures using these data. The published industries do not, however, correspond to our industries so there are some differences compared to our industries.

Before looking at the data by industry, note that an early study of these data was by Swann. Exhibit 17 is drawn from his work and shows the broader pattern of reported information networks which his analysis reveals. Each circle corresponds to a particular potential information source. As the top left figure shows, some firms have literally no external networks, 8% have networks just with companies, 22% with companies and intermediates and 36% also with the research base.

Exhibit 17 Patterns of Information Networks of UK Businesses



Source: Swann (2009)

Turning to the data, Exhibit 18 presents the overall co-operation behaviour of UK firms by industry, during 1998 to 2008. It includes co-operation agreements on any innovation activities, with a number of partners. The survey asks about co-operation agreements with businesses within the same enterprise group; suppliers of equipment, materials; clients and customers; competitors or other businesses in the industry; consultants, commercial labs, or private R&D institutes; universities or other higher education institutions, government or public research institutes. On average, over time and industries, 17% of UK businesses are engaging in co-operative agreements with different types of partners. Exhibit 18 shows that, overall, the share of UK firms engaging in co-operative agreements has increased, the highest increase occurring after 2006. This trend is consistent with the opening up of the innovation process that occurred in recent years. We also see a great heterogeneity between different industries. On average, the more "open" industries are Electricity, Gas and Water Supply, followed by the manufacturing sector, however the increase in the share of co-operating firm in manufacturing is higher.

Exhibit 18 Co-operation by Industry – CIS3 to CIS6

	1998-2000	2002-2004	2004-2006	2006-2008	Average
Agriculture, Fishing and Mining	12%	11%	15%	20%	**15%**
Manufacturing	14%	19%	20%	36%	**22%**
Electricity, Gas and Water Supply	27%	14%	23%	31%	**24%**
Construction	6%	11%	8%	20%	**11%**
Wholesale & Retail Trade, Hotels and Rest., Transport & Com.	8%	11%	9%	21%	**12%**
Financial Services	9%	16%	13%	26%	**16%**
Business Services	11%	18%	14%	31%	**18%**
Personal Services	n.a.	n.a.	16%	21%	**18%**
Average	**12%**	**14%**	**15%**	**26%**	**17%**

Source: ONS

In this study, we are interested in the interactions between businesses and the public science base. Exhibit 19 presents the share of UK firms that have engaged in a co-operative agreement with universities, higher education institutes (HEIs) and/or public research organisations (PROs). As reported by previous research (Cosh et al., 2006; Laursen & Salter, 2004), the share of UK firms that co-operate with public science base is quite low, and more importantly, there is no clear upward trend in recent years. Again, firms performing in the Electricity, Gas and Water Supply industries have the higher share on average. Around

8-9% of manufacturing firms are also engaging in co-operative agreements with the public science base, followed by Business Services, confirming the increasing interaction between business services firms and universities, HEIs and PROs (Mina et al., 2013).

Exhibit 19 Co-operation with Universities, HEIs and/or PROs by Industry – CIS3 to CIS6

	1998-2000	2002-2004	2004-2006	2006-2008	Average
Agriculture, Fishing and Mining	7%	6%	9%	8%	8%
Manufacturing	6%	9%	8%	11%	9%
Electricity, Gas and Water Supply	13%	8%	14%	8%	11%
Construction	2%	5%	2%	7%	4%
Wholesale & Retail Trade, Hotels and Rest., Transport & Com.	2%	4%	3%	6%	4%
Financial Services	1%	4%	3%	5%	3%
Business Services	5%	10%	6%	11%	8%
Personal Services	n.a.	n.a.	1%	4%	2%
Average	5%	7%	6%	7%	6%

Source: ONS

However, co-operation agreements are not the only way in which businesses can interact with the public science base. The UK Innovation Survey also asks about the sources of information related to businesses' innovation activities. Exhibit 20 presents the share of UK firms that use universities, higher education institutes and/or government or public research institutes as a source of information for their innovation activity. Indeed, the share of businesses that use the public science base as an information source is much higher compared to formal co-operation agreements they are engaged in. Previous literature has highlighted the importance of informal means of interactions in the relationship between universities and firms (Grimpe and Hussinger, 2008; Helmers and Rogers, 2010).

Exhibit 20 Universities, HEIs and/or PROs as Source of Information by Industry – CIS3 to CIS6

	1998-2000	2002-2004	2004-2006	2006-2008	Average
Agriculture, Fishing and Mining	17%	30%	32%	18%	24%
Manufacturing	25%	36%	34%	29%	31%
Electricity, Gas and Water Supply	36%	28%	40%	26%	32%
Construction	12%	27%	23%	15%	19%
Wholesale & Retail Trade, Hotels and Rest., Transport & Com.	12%	20%	18%	15%	16%
Financial Services	11%	25%	18%	14%	17%
Business Services	20%	36%	31%	24%	28%
Personal Services	n.a.	n.a.	18%	11%	15%
Average	19%	29%	27%	19%	23%

Source: ONS

Previous literature has also highlighted the role of firms' absorptive capacity in the search for, adoption and adaption of external knowledge. Indeed, when we look at the Exhibit 21, where we present the share of R&D active UK firms engaged in co-operation agreements with the public science base, we note that, although not as high as informal means, the share of firms co-operating with universities, HEIs and PROs are higher for firms that are actively investing in R&D.

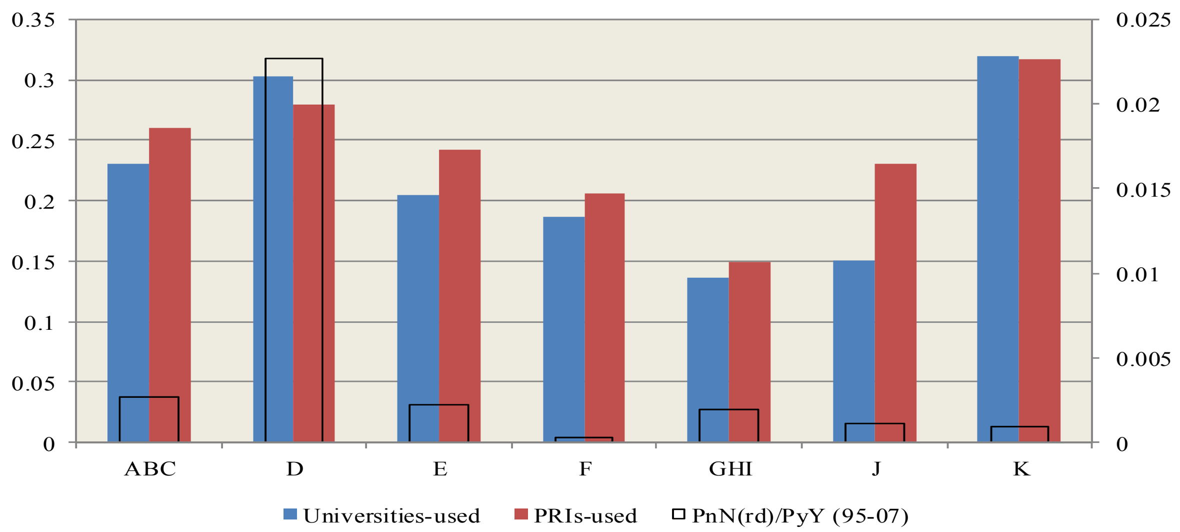
Finally, we compare some of these data with R&D intensity.

Exhibit 21 Co-operation with Universities, HEIs and/or PROs by Industry – R&D active firms only– CIS3 to CIS6

	1998-2000	2002-2004	2004-2006	2006-2008	Average
Agriculture, Fishing and Mining	12%	10%	15%	13%	13%
Manufacturing	11%	12%	10%	16%	12%
Electricity, Gas and Water Supply	29%	21%	21%	13%	21%
Construction	5%	9%	3%	11%	7%
Wholesale & Retail Trade, Hotels and Rest., Transport & Com.	5%	7%	3%	10%	6%
Financial Services	2%	6%	5%	7%	5%
Business Services	10%	14%	8%	17%	12%
Personal Services	n.a.	n.a.	1%	9%	5%
Average	11%	12%	8%	12%	11%

Source: ONS

Exhibit 22 Company Relations with Universities and R&D Intensity.



Note: industries are: ABC= food, agriculture, mining, D= manufacturing, E=utilities, F=construction, GHI=retail, hotels, J=financial intermediation, K=business services. Data averaged 91-07.

Source: BIS CIS survey, http://webarchive.nationalarchives.gov.uk/+/http://www.bis.gov.uk/policies/science/science-innovation-analysis/cis.

To bring this together, Exhibit 22 shows**,** in the coloured in bars, by industry, the fraction of firms reporting that they used "universities or other higher education institutions" and "government or public research institutes" as sources of information for innovation (shown on the left hand scale is the weighted fraction of the industry firms who replied yes to this question). The unshaded bars and the right scale, show the R&D intensity of the industry. As the picture shows, manufacturing and business services use universities and PRIs most intensively, even though business services does relatively little R&D. In addition, the data confirms the rather small fraction of firms reporting using these sources of information.

4.3 The transition to econometric work

In taking equation (1) to the data, we are confronted with a number of issues. Proceeding term by term, we first have to build $\Delta \ln R_i$ which we do with a series of conventional assumptions about depreciation and initial stocks. Second, we have to build the change in the stock of outside private knowledge. To keep things manageable we do this by aggregating other industries $\Delta \ln R_i$ Third, we have to measure $\Delta \ln R^{PUB}$and also P, the extent to which public knowledge is contributing to the particular industry. Regarding P, since the research council sector spend is primarily technical and scientific (e.g. arts funding is almost negligible) then the degree to which the industry itself is science and technology knowledge intensive might be an important determinant of how potentially applicable such knowledge is (for example, engineering research might be better suited to manufacturing industry rather than financial services). This suggests interacting public spending with own-industry R&D intensity. On the other hand, one might argue that all information is potentially part of the knowledge pool and so simply enter $\Delta \ln R^{PUB}$.

Fourth, as mentioned above, we have to measure the coefficients, which are, here the elasticity of TFP growth with respect to $\Delta \ln R$. As is well-known, Cohen and Levinthal (1989, 1990) suggest that absorptive capacity might depend on own-firm R&D spend ($P^N N$) in our notation. But, they also suggest that γ depends on other factors, β, "*that reflect the characteristics of outside knowledge that make R&D more or less critical to the maintenance and development of absorptive capacity".* As an example, they suggest that it might depend upon (a) the complexity of outside knowledge and (b) the extent to which outside knowledge is targeted to the firm. So for example, highly complex "blue skies" knowledge produced by a university might require a lot of firm R&D investment to be absorbed. Finally, β might also depend upon the speed of advance of a field, since more resources might be needed to absorb a faster moving field of study.

All this makes the determination of P complicated. If public R&D is blue sky, absorption of it might need private R&D. If it is applied, then absorption of it might need other private sector funding, e.g. in terms of training or involvement in other integration assets but most important from our point of view might not need private R&D at all. Indeed, if the costs of private sector R&D are measured correctly it should have no effect on ΔlnTFP anyway. Indeed, if this is the case any effect on R&D will measure only the *excess* returns to such interaction (which could be zero, positive, or, if mismeasurement, negative.

We have in addition, as set out above, survey information on whether firms co-operate with universities or public research organisations and whether they get their information from them.

We therefore proceed as follows. First, we simplify (1) by writing out the γ and ΔlnR(PUB) terms explicitly, using a perpetual inventory model to substitute out ΔlnR(PUB) and assuming the deprecation rate of public knowledge (δ(PUB)) is zero, giving

$$\Delta \ln TFP_{it} = \alpha_{it}\left(\Delta \ln R_{it}^{PRIV}\right) + \beta_{it}\left(\mathbf{M}\Delta \ln R_{\_i,t}^{PRIV}\right) + \rho_{it}\mathbf{P}\left(\frac{N_t^{PUB}}{G_{it}}\right) \tag{2}$$

Next we have to model ρ and P. Both are likely to depend upon similar variables: for example, the amount of R&D might affect both the rate of return, via absorptive capacity but also P. Trying lots of interactions resulting in an equation that was just too collinear to estimate and hence we settled on a simple equation of the form

$$\Delta \ln TFP_{it} = \alpha_{it}\left(\Delta \ln R_{it}^{PRIV}\right) + \beta_{it}\left(\mathbf{M}\Delta \ln R_{\_i,t}^{PRIV}\right) + \left(\rho_0 + \rho_1 X_{it}\right)\left(\frac{N_t^{PUB}}{G_{it}}\right) \tag{3}$$

Where for X we tried a number of different variables. We tried private sector research intensity, X= $P_N N^{R\&D,\ PRIV} / P_G G_i$ where $P_N N^{R\&D,\ PRIV}$ is private R&D spend and $P_G G_{it}$ is industry gross output and X=COOP where COOP are the various co-operation measures.

We take a number of other steps in taking our model to the data. First, we wish to long difference our TFP data since short differences (say annual) render ΔlnTFP very noisy due to measurement error in TFP. We experimented with a number of lags and found that the results with three-year differences were representative that is $\Delta_3$lnTFP=lnTFP(t)-lnTFP(t-3). Second, it is plausible to believe that public science investment takes time to spill over into the private sector. Much science-based funding is for projects that take a number of years to complete and involve post-docs and PhD students who take time to build skills and make discoveries that can be absorbed by the private sector. Since we have a three-year difference for TFP, a *contemporaneous* effect from public investment would be tested using the sum of investment over that three-year span, i.e. Σ_3(N(Pub)/G)(t)= [(N(Pub)/G)(3) (t)+ (N(Pub)/G)(3)(t-1)+ (N(Pub)/G)(3)(t-2)]. A lagged effect, of three years say, would use Σ_3(N(Pub)/G)(t-3).

That said, our data spans 1992-2007 (we rely on the input-ouput tables and therefore 1992 is the furthest we can go back without interpolating across long intervals between pre-1992 IO table releases). Thus if we use a three year difference for TFP we start in 1995, and if we also use a three year lag in Σ_3(N(Pub)/G)(t) we have to start in 1998: as a result losing six out of 15 observations. It turns out, however, in our data that N(Pub) and G are highly serially correlated (the correlation between Σ_3(N(Pub)/G)(t-3) and (N(Pub)/G)(t-3) is 0.98). Thus in our regressions we use (N(Pub)/G)(t-3) which preserves the three-year lag, but does not lose significant degrees of freedom (note that if we use Σ_3(N(Pub)/G)(t) we get very similar results: we show some experiments below).

We construct the M matrix by weighting other industry $\Delta \ln R_{\_i}^{PRIV}$ by its labour transition weight in relation to industry i (so that for example, if few workers from agriculture move to manufacturing, $\Delta \ln R^{PRIV}$ in agriculture gets a low weight in computing $\Delta \ln R^{PRIV}_{\_i,\,t}$ for manufacturing). Denoting the labour transition weights by ω, and Δ_3 a three year time difference, our estimating equation is then

$$\Delta_3 \ln TFP_{it} = \alpha_{it}\left(\Delta_3 \ln R_{it}^{PRIV}\right) + \beta_{it}\left(\Sigma\omega_{i,t}\Delta_3 \ln R_{\_i,t}^{PRIV}\right) + \left(\rho_0 + \rho_1 (X_{it-3} / \Sigma X_{it-3}\right)\left(\frac{N^{PUB}}{G_i}\right)_{t-3} + \lambda_i + \lambda_t + \varepsilon_{it} \quad (4)$$

Where X_{it} is entered as a fraction of its total value in that year, for reasons explained below.

Noting that the equation includes industry and time means, what does this equation say? If $\rho_0 > 0$, it says that in an industry where the science spend intensity rises above its time and industry average, then $\ln TFP_{it}$ rises three years later and that the rate of return to N^{PUB} is ρ_0. If $\rho_1 > 0$, it says that in an industry where the science spend intensity rises above its time and industry average, then $\ln TFP_{it}$ rises three years later but by more if the industry has a higher value of X/ΣX (where X is either private R&D intensity or university-industry co-operation relative to the average). In this case the rate of return depends upon the value of X_i /ΣX in the industry, so if it is X_K /ΣX on average in industry K, the rate of return is $\rho_0 + \rho_1 X_K$ /ΣX (thus the average rate of return is just ρ_1 which is why we enter X_i /ΣX so that we can read off the average directly).

When in practice we estimate (1) using panel data, we have to be careful of a number of issues. The panel data format imposes a constant ρ_0 across all industries (we can allow ρ_0 to vary by industry but would start to exhaust degrees of freedom). Now, note that the economy-wide impact of N^{PUB} requires us to sum ρ_0 across all industries. Thus suppose that it is high in one industry (say manufacturing) and very low in another (say construction). Imposing a common coefficient across both industries and estimating by fixed effects gives a single value for ρ_0 which might be misleading, particularly if the true ρ_I is correlated with the regressor.[7] If we then add that estimated ρ_0 across all industries we might compound the error.

Matters are somewhat improved in the equation where we allow ρ_1 to vary by industry, although if we mis-specify the variation then we run the risk of a bias in the same way. An additional factor is presentational: if we express the rate of return for each industry as un-normalised, then it is $\rho_1 X_i$ and the rate of return to all industries is $\rho_1 \Sigma X_i$. Thus the common coefficient-estimated industry rate of return will be the total rate of return only if we specify the interaction as $\rho_1(X_i/\Sigma X_i)$. This is presentationally convenient, but imposes a particular form of dependence of ρ_i on X_i.

With this in mind, we estimate (1) above by modelling with ($\rho_0+\rho_1 X_i/\Sigma X_i$). We will be cautions about ρ_0 given the discussion above, and when we use either industry private R&D intensity or co-operation to model $\rho_1(X_i/\Sigma X_i)$ they are both normalised on their year summations.

4.4 Data on TFP, R&D and other controls

In Haskel and Wallis (2013) we looked at the spillovers from research council funded R&D by studying the relation between market sector ΔlnTFP, private sector performed R&D and research-council funded R&D. In this paper we use different data. As will be clear from the above, we use industry data, not data for the market sector as a whole. But we also use slightly different R&D data.

An important issue in understanding any R&D is the performer/funder distinction (see e.g. Hughes and Martin, 2012). To see this, Exhibit 23 sets out 2011 R&D data taken from the official national accounts data (Gross Expenditure on R&D, GERD), which shows the sector providing the funds, in the rows and performing the work, in the columns.

[7] Juhl and Lugovskyy (2014) interpret the fixed effects estimate of a parameter as a weighted average of the OLS estimate of each cross-sectional unit, with the units with the most intra-group variation in the Xs getting the highest weight. They then show a 2 unit example where the true slopes are +1 and -1, but the intra-group variation in the -1 group is twice that in the +1 group. The fixed effect estimate of the slope is -3/5 which does not even correspond to the average of the two which is 0.

Exhibit 23: R&D performed in the UK in each sector according to source of funding, 2011

CURRENT PRICES	Sector carrying out the work						£ million
	Government	Research Councils	Higher Education	Business Enterprise	Private Non-Profit	**Total**	Abroad
Sector providing the funds							
Government	977	86	406	1,601	68	3,138	531
Research Councils	47	819	1,979	11	86	2,942	188
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	2,003
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, 2011 (http://www.ons.gov.uk/ons/dcp171778_302928.pdf), , Notes to table:

1. Columns 1+2= GovERD, column 3=HERD, column 4=BERD and column 5=PNP. These columns sum to GERD shown in column 6.
2. - denotes nil, figures unavailable or too small to display.

To read the exhibit, consider the far right bottom corner which shows that in 2011 total spend was £27.380bn. 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 and £7.127bn was performed by government departments, research councils and higher education. 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's element which provides £2.257bn of funding of R&D which is performed and funded in 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 research institutes, (£47m+£819m=)£866m. Third, "government departments" (not including research councils) funded £3.138bn of R&D, of which just over 50%, £1.601bn, is performed in the business sector , and just over 33%, (£977m+£86m=)£1.063bn, is performed by government departments, that is by public research institutes and government owned laboratories.

All this shows that government funding of R&D is not the same as government performance of R&D. National accounts practice is to allocate an asset to the owner of that asset, which is usually taken to be the agent funding it. This suggests we term public R&D that funded by the public. There are two issues that arise in R&D however. First, the performer of R&D might hand over the ownership to a funder, but still would have presumably built up knowledge capital from the very performance of the R&D. Second, ONS has recently extended its R&D questionnaire to ask firms about both the funding and also the ownership of R&D. They find that 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.

We proceed as follows Goodridge et al. (2014) provide some more extensive tests of robustness, the results here are representative). We use essentially the performer concept. So, to construct private R&D, we use £17.408bn, 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%), we allocate that to business, either because they perform it and hence learn and because the ONS survey indicates a large fraction 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. Finally, we allocate private R&D to its industry according broadly again to sector of performance.

Exhibit 24 below shows our data. TFP growth is highest in business services and retail, but they get relatively low outside R&D to their sectors. Industry variation in public R&D intensity comes from industry variation in G. As we saw above, manufacturing has the highest private R&D intensity, and utilities has the highest co-operation.

Exhibit 24: Regression: data descriptives

_	ΔlnTFP	ΔlnR(i)	SwΔlnR(-i)	(RC+HE)/G	(RC+HE+Gov)/G	RD(priv)/G	COOP
Manufacturing	0.0053	0.0475	0.0031	0.0070	0.0130	0.0227	0.0750
Utilities	0.0058	-0.0179	0.0138	0.0589	0.1093	0.0022	0.1142
Construction	0.0004	0.0060	0.0065	0.0255	0.0479	0.0003	0.0319
Retail, hotels	0.0077	0.0640	0.0024	0.0074	0.0139	0.0020	0.0300
FinSvcs	0.0069	0.0774	0.0043	0.0229	0.0432	0.0011	0.0242
Bus Services	0.0089	0.0731	0.0045	0.0170	0.0322	0.0009	0.0696
Average	**0.0058**	**0.0417**	**0.0058**	**0.0231**	**0.0433**	**0.0049**	**0.0575**

Notes: The exhibit shows averages for all variables, by industry for 1995-07. "Δln" stands for three year log difference, divided by 3. Columns are: 1=ΔlnTFP=change in log gross output-based TFP. 2=ΔlnR(i)= growth in private sector R&D capital, 3= ΣωΔlnR(i)= , is outside industry ΔlnK(R&D) weighted by the fraction of outside industry workers moving to industry i over the period; in other columns, RC, HE, Gov are values of R&D performed in research council, HE and Government sectors (all net of business R&D performed in these sectors). G= industry gross output, RD(Priv)= value of private R&D performed, COOP is fraction of firms in the industry co-operating with government or universities. Note ΔlnTFP is here gross output based, which is less then value added based ΔlnTFP. Note too that the simple average of ΔlnTFP for these market sector industries, which is 0.58%, does not correspond to value added ΔlnTFP for the whole market sector: for that one must construct a Hulten-Domar weighted average of ΔlnTFP which comes to 1.3%pa.

4.5 Regression analysis of the impact of public R&D on sectoral TFP

Exhibit 25 shows our regression results. Fixed effects were never significant and so we used random effects. In addition, the linear term in N^{PUB}/G was never significant and so is not reported here. The table reads as follows. The first row in the table show consistently positive and statistically significant effects on TFP of growth in R&D capital within the industry (ΔlnR (PRIV)(i,t)). The second row shows that the coefficient on the weighted growth of R&D capital stock outside the industry (ΣωΔlnR(PRIV)(_i,t)) varies. It is significantly positive in column 1 and insignificantly positive in column 2, but insignificantly negative in column 3.

Exhibit 25: Regression estimates of market sector industry TFP growth (dependent variable: Δ3lnTFPit)

VARIABLES	(1) R&D	(2) R&D	(3) CO-OP	(4) CO-OP	(5) CO-OP
Δ(3)lnK(priv)(R&D), i	0.10	0.11	0.08	0.09	0.10
	(4.16)	(2.72)	(3.48)	(6.59)	(2.60)
Δ(3)lnK(priv)(R&D), _i	0.82	0.92	-0.68		
	(2.41)	(1.78)	(-1.73)		
{[(RC+HEFC)/G]*R&D(priv)/G}(t-3)	0.41				
	(3.00)				
{[(RC+HEFC)/G]*R&D(priv)/G}(t-6)		0.82			
		(3.30)			
{[(RC+HEFC+GovRD)/G]*CO-OP}(t-3)			0.36	0.21	
			(5.62)	(4.59)	
{[(RC+HEFC+GovRD)/G]*CO-OP}(t-6)					0.20
					(2.09)
Observations	78	60	78	78	60
Number of ind	6	6	6	6	6
F test for equal fixed effects	F(5, 57) = 2.17 , Prob > F = 0.07		F(5, 57) = 0.96 , Prob > F = 0.45		
F(5, 57) = 0.96 , Prob > F = 0.4476					

Notes: The dependent variable is the three year change in log gross output-based TFP. G is real gross output. Robust t statistics are shown in brackets. The sample period is 1995-2007, 6 industries excluding agriculture. All regressions include time effects: estimation is by random effects: tests for equality of fixed effects are reported in the lowest row of the table. All change variables are three year differences: the public R&D /Y variables are dated t-3. The three year differenced variables are all divided by three so that the coefficients on them and the public R&D /GO variables can be interpreted as annual elasticities and rates of return. The outside R&D variable in row 2 is outside industry ΔlnK(R&D) weighted by the fraction of outside industry workers moving to industry i over the period. Private R&D is that performed in the business sector. RC, HEFC, GovRD are research council HEFC and

Government performed R&D (all net of business R&D performed in these sectors). In rows 4 and 6 R&D(priv)/Y and CO-OP are divided by their year sums.

Rows 1 and 2 show the results of experimenting with two measures of public R&D spend. Row three enters the sum of research council and HEFC performed R&D (RC and HEFC) as a proportion of industry gross output G_{it} [8] interacted with private industry R&D intensity (R&D(priv)): this is all lagged three years (and as explained above, (R&D(priv)) is divided by its annual sum over all industries). The interacted term is statistically significant. Column 2 lags it 6 years and finds a larger point estimate.

The final three rows replace the public R&D spend variable by the CO-OP variable (again divided by its annual sum over all industries) as an interaction. Recall however that this variable is co-operation with universities and public research institutes. So in addition to RC and HEFC we include R&D performed in government again net of business financed R&D performed in government (GovRD). Once again, there are statistically significant effects on the interacted variable.

What are the implied rates of return to public R&D? Columns 1 and 2 suggest a return of 41% and 82%, so this suggests the results are sensitive to lags. Longer lags give bigger returns. Columns 3, 4 and 5 are less variable, with returns of 20 and 21% in columns 4 and 5 which drop the statistically insignificant outside R&D term which was included in column 3.

To put some numbers on these effects we do the following. Exhibit 24 suggests that research councils, HEFC and government perform R&D at a value of around £9bn. Suppose then that we raised that budget by 5%, which is £450m. Taking the results in column 5, ΔlnTFP in the market sector would then rise by 0.20* (0.450bn)=£90m in that year. This is assumed to be a permanent rise in the level of output if public R&D is assumed not to depreciate. Thus on this assumption, a one-off increase in public spending generates an infinitely-lived rise in the level of knowledge capital and so an infinitely-lived higher output. The present discounted value of £90m, at 5%, is £1.8bn.

(An alternative way of expressing this is that RC+HEFC+GovRD is around £9bn in 2007, and the level of market sector GVA, about £1,000bn. Thus the induced rise in $\Delta \ln TFP^{Q}$ by increasing the £9bn by 5% is 0.20*(£9bn*0.05)/1,000bn = 0.00009: i.e. market sector $\Delta \ln TFP^{Q}$, would rise by 0.009%).

A rate of return to public spending of 20%, other things equal, is relatively high for public projects. In judging this figure, there are two things to bear in mind. First, other existing literature and the results of the initial part of this report imply that increased public R&D is associated with more private R&D. If

[8] RC and HEFC are, as described above, net of any private funding performed by research councils and HEFC. Both are deflated by the GDP deflator, whereas G is deflated by the own-industry gross output deflator.

this is causal, then these rates of return are a lower bound since such spending might "crowd in" private R&D. Second, public spending on the science base could be judged relative to the alternative, which in this case might be provision of R&D tax credits. These might spur private R&D. The relative efficiency of spending on tax credits would have to depend upon the extent to which such spending lowered the cost of private R&D and then on the subsequent rate of return on any resulting increase in private R&D spend.

5 Conclusion

What then are the implications of all this for the science budget?

First, we have shown that there is a wide variety of positive impact links between the science base and the private sector. Moreover, there appears to be a "crowding in" effect of public sector R&D on domestic and foreign R&D activities in the UK.

Second, a further and related key finding is that the link from the science budget to TFP growth in an industry depends crucially on the R&D performance, or co-operation with the university sector, of the industry itself. This can be interpreted as the joint effect of an appropriate scaling of the public science budget to get the usable knowledge stock for each industry, and as a measure of the absorptive capacity of the industry. These can be taken with the results from the first part of the report to suggest a virtuous circle regarding private and public sector R&D.

These findings are consistent with a wide range of evidence suggesting a complementary relationship between industry and public sector R&D. Science and innovation policy is not and should not be seen as a zero-sum game in which they are substitutes.

Bibliography

Abramovsky, L., & Simpson, H. (2011). Geographic proximity and firm-university innovation linkages: evidence from Great Britain. *Journal of Economic Geography*, 11(6), 949–977. doi:10.1093/jeg/lbq052

Abramovsky, Laura, Harrison, R., & Simpson, H. (2007). University Research and the Location of Business R&D. *The Economic Journal*, 117(519), C114–C141. doi:10.1111/j.1468-0297.2007.02038.x

Alexander, A. (2009) *RCUK/UUK Review of the Impact of Full Economic Costing on the UK Higher Education Sector: A Report prepared for Research Councils UK and Universities UK by a Panel chaired by Professor Alan Alexander*, RCUK and UUK, April.

Alexy, O. and Salter, A. (2014). 'The nature of innovation' in Dodgson, M., Phillips, N., & Gann, D. (eds), *Oxford handbook of innovation management,* Oxford: Oxford University Press.

Almeida, P. (1996). Knowledge Sourcing by Foreign Multinationals: Patent Citation Analysis in the U.S. Semiconductor Industry. *Strategic Management Journal*, 17, 155–165.

Anselin, L., Varga, A., & Acs, Z. (1997). Local Geographic Spillovers between University Research and High Technology Innovations. *Journal of Urban Economics*, 42(3), 422–448. doi:10.1006/juec.1997.2032

Atkinson, R. D. (2007). How Do Companies Choose Where to Build R&D Facilities ? *presented before the Committee on Science and Technology Subcommittee on Technology and Innovation U . S . House of Representatives*, 1–12.

Audretsch, D. B., & Feldman, M. P. (1996). Innovative clusters and the industry life cycle. *Review of Industrial Organization*, 11(2), 253–273. doi:10.1007/BF00157670

Blanc, H., & Sierra, C. (1999). The internationalisation of R&D by multinationals: a trade-off between external and internal proximity. *Cambridge Journal of Economics*, (June 1996), 187–206.

Cantwell, J. (2009) 'Location of the Multinational Enterprise', *Journal of International Business Studies* 40(1): 35-41.

Cohen, W.M. and Levinthal, D.A. (1989). 'Innovation and Learning: The Two Faces of R&D', *Economic Journal* 99 (397): 569-596.

Cohen, W.M. and Levinthal, D.A. (1990). 'Absorptive Capacity: A New Perspective on Learning and Innovation', *Administrative Sciences Quarterly* 35(1): 128-152.

Cohen, W., Nelson, R. R., & Walsh, J. P. (2002). Links and impacts: the influence of public research on industrial R&D. *Management science*, 48(1), 1–23.

Cosh, A., Hughes, A., & Lester, R. (2006). UK PLC: just how innovative are we? Findings from the Cambridge-MIT Institute International Innovation Benchmarking Project. *The Cambridge-MIT Institute*, (December).

Demirbag, M., & Glaister, K. W. (2010). Factors Determining Offshore Location Choice for R&D Projects: A Comparative Study of Developed and Emerging Regions. *Journal of Management Studies*, 47(8), 1534–1560. doi:10.1111/j.1467-6486.2010.00948.x

Driffield, N., & Love, J. (2007). Linking FDI motivation and host economy productivity effects: conceptual and empirical analysis. *Journal of International Business Studies*, 38(3), 460–473.

Driffield, N., & Love, J. J. H. (2005). Who gains from whom? Spillovers, competition and technology sourcing in the foreign-owned sector of UK manufacturing. *Scottish Journal of Political Economy*, 52(5), 663–687. doi:10.1111/j.1467-9485.2005.00361.x

Dunning, J. H. (1977). *Trade, location of economic activity and MNE : A search for an eclectic approach*. In Ohlin, B., P.O. Hesselborn & P.J. Wijkman (Eds.), The International Allocation of Economic Activity, MacMillan, London.

Dunning, John H. (2000). The eclectic paradigm as an envelope for economic and business theories of MNE activity. *International Business Review*, 9(2), 163–190. doi:10.1016/S0969-5931(99)00035-9

Florida, R. (1995). Toward the learning region. *Futures*, 27(5), 527–536.

Florida, Richard. (1997). The globalization of R&D: Results of a survey of foreign-affiliated R&D laboratories in the USA. *Research policy*, 26, 85–103.

Foray, D. and Lissoni, F. (2009) University research and public-private interaction in Hall, B.H. and Rosenberg, N. (eds) Handbook of the economics of innovation, North Holland.

Gassmann, O., & von Zedtwitz, M. (1999). New concepts and trends in international R&D organization. *Research Policy*, 28(2-3), 231–250. doi:10.1016/S0048-7333(98)00114-0

Girma, S., & Görg, H. (2003). Foreign Direct Investment, Spillovers and Absorptive Capacity: Evidence from Quantile Regressions. *SSRN Electronic Journal*. doi:10.2139/ssrn.410742

Girma, S., & Görg, H. (2007). The Role of the Efficiency Gap for Spillovers from FDI: Evidence from the UK Electronics and Engineering Sectors. *Open Economies Review*, 18(2), 215–232. doi:10.1007/s11079-007-9031-y

Goodridge, P., Haskel, J., & Wallis, G. (2014), *The Contribution of Science to UK Productivity Growth*. Forthcoming.

Grimpe, C., & Hussinger, K. (2008). Formal and informal technology transfer from academia to industry: complementarity effects and innovation performance. *ZEW-Centre for European Economic*, (08).

Guellac, D. and van Pottelsberghe de la Potterie, B. (2004). 'From R&D to productivity growth: do the institutional settings and the source of funds of R&D matter?', *Oxford Bulletin of Economics and Statistics*, Vol. 66(3): 353-378.

Guinet, J., & Backer, K. De. (2008). *The internationalisation of business R&D: evidence, impact and implications*. OECD.

Hakanson, L., & Nobel, R. (1993). Determinants multinationals of foreign R&D in Swedish multinationals. *Research Policy*, 22, 397–411.

Hall, B. (2011). The internationalization of R&D. *UNU-MERIT Working Paper Series*, 049(31).

Harhoff, D. (1999). Firm formation and regional spillovers-evidence from Germany. *Economics of Innovation and New Technology*, (October 2013), 37–41.

Harris, R. and Li, C. (2008). 'Exporting, R&D and absorptive capacity in UK establishments', *Oxford Economic Papers* 61: 74-103.

Harris, R., Li, C. and Moffat, J. (2013) 'The Impact of Higher Education Institutions-Firm Knowledge Links on Establishment-Level Productivity in British Regions, *Manchester School* 81(2): 143-162.

Haskel, J., & Wallis, G. (2013). Public support for innovation, intangible investment and productivity growth in the UK market sector. *Economics Letters 119*(2): 195-198.

Haskel, J. and Wallis, G. (2010). Public Support for Innovation, Intangible Investment and Productivity Growth in the UK Market Sector, IZADP Discussion Paper Series No. 4772, February, Imperial College London. http://ideas.repec.org/p/iza/izadps/dp4772.html.

Helmers, C., & Rogers, M. (2010). The impact of university research on corporate patenting. *SERC Discussion Paper N:54*, (September).

Hughes, A., Kitson, M., Bullock, A. and Milner, I. (2013). *The Dual Funding Structure for Research in the UK: Research Council and Funding Council Allocation Methods and the Pathways to Impact of UK Academics*, A Report from the Centre for Business Research and the UK~IRC for the Department for Business, Innovation and Skills.

Hughes, A. and Kitson, M. (2013). *Connecting with the Ivory Tower: Business Perspectives and Knowledge Exchange in the UK*, London and Cambridge: UK~IRC and NCUB.

Hughes, A. and Kitson, M. (2012). Pathways to Impact and the Strategic Role of Universities: new evidence on the breadth and depth of university knowledge exchange in the UK and the factors constraining its development, *Cambridge Journal of Economics,* Special Issue, 36: 712-750.

Hughes, A. and Martin, B.R. (2012). *Enhancing Impact: The Value of Public Sector R&D*, CIHE and UK~IRC, Cambridge and London.

Hughes, A. and Mina, A. (2012). The UK R&D Landscape, Revised March, UK~IRC and CIHE, Cambridge and London.

Iammarino, S. and McCann, P. (2013) *Multinationals and Economic Geography: Location, Technology and Innovation*, Chelthamham: Edward Elgar.

Ito, B., & Wakasugi, R. (2007). What factors determine the mode of overseas R&D by multinationals? Empirical evidence. *Research Policy*, 36(8), 1275–1287. doi:10.1016/j.respol.2007.04.011

Jaffe, A., Trajtenberg, M., & Henderson, R. (1993). Geographic Localisation of Knowledge Spillovers as Evidenced By Patent Citations. *Quarterly Journal of Economics*, 108(3), 577–598.

Jeaumotte, F. and Pain, N. (2005a) 'From ideas to development: the determinants of R&D and patenting', OECD Economics Department Working Paper No. 457, Paris: OECD.

Jeaumotte, F. and Pain, N. (2005b) 'Innovation in the Business Sector', OECD Economics Department Working Paper No. 459, Paris: OECD.

Juhl, T. and Lugovskyy, O, (2014) A Test for Slope Heterogeneity in Fixed Effects Models, Econometric Reviews, 33:8, 906-935,

Kuemmerle, W. (1999). The drivers of foreign direct investment into research and development: an empirical investigation. *Journal of international business studies*, 30(1), 1–24.

Laursen, K., & Salter, A. (2004). Searching high and low: what types of firms use universities as a source of innovation? *Research Policy*, 33(8), 1201–1215. doi:10.1016/j.respol.2004.07.004

Le Bas, C., & Sierra, C. (2002). Location versus Home country Advantages in R&D Activities: Some Further Results on Multinationals Locational Strategies. *Research Policy*, 31(4), 589–609.

Lewin, A. Y., Massini, S., & Peeters, C. (2009). Why are companies offshoring innovation? The emerging global race for talent. *Journal of International Business Studies*, 40(6), 901–925. doi:10.1057/jibs.2008.92

Martin, B.R. (2012). Are universities and university research under threat? Towards an evolutionary model of university speciation, *Cambridge Journal of Economics*, Special issue 36(3): 543-565.

Odagiri, H., & Yasuda, H. (1996). The determinants of overseas R&D by Japanese firms: an empirical study at the industry and company levels. *Research Policy*, 25, 1059–1079.

Patel, P., & Vega, M. (1999). Patterns of Internationalisation of Corporate Technology: Location versus Home Country Advantages. *Research Policy*, 28, 145–155.

Pearce, R. D. (1999). Decentralised R & D and strategic competitiveness : globalised approaches to generation and use of technology in multinational enterprises ž MNEs /.

Pearce, R., & Papanastassiou, M. (1999). Overseas R&D and the strategic evolution of MNEs: evidence from laboratories in the UK. *Research Policy*, 28(1), 23–41. doi:10.1016/S0048-7333(98)00104-8

Rilla, N., & Squicciarini, M. (2011). R&D (Re)location and Offshore Outsourcing: A Management Perspective. *International Journal of Management Reviews*, 13(4), 393–413. doi:10.1111/j.1468-2370.2011.00297.x

Swann, P. (2009), *Innovators and the Research Base – An Exploration using the 4th Community Innovation Survey (CIS4),* DIUS Research Paper, 09-10 May.

Thomson, R. (2013). National scientific capacity and R&D offshoring, *Research Policy* 42: 517– 528.

Thursby, J. G., & Thursby, M. (2006). *Here or There ? A survey of factors in multinational R&D location*. Washington, D.C: National Academic Press.

van Pottelsberghe de la Potterie, B. and Lichtenberg, F. (2001). Does Foreign Direct Investment Transfer Technology Across Borders? *The Review of Economics and Statistics*, 83(3), 490–497.

von Zedtwitz, M., & Gassmann, O. (2002). Market versus technology drive in R&D internationalization: four different patterns of managing research and development. *Research Policy*, 31(4), 569–588. doi:10.1016/S0048-7333(01)00125-1

von Zedtwitz, M., Gassmann, O., & Boutellier, R. (2004). Organizing global R&D: challenges and dilemmas. *Journal of International Management*, 10(1), 21–49. doi:10.1016/j.intman.2003.12.003

Wakeham, W. (2010) *Financial Stability and Efficiency in Full Economic Costing of Research in UK Higher Education Institutions: Report of RCUK/UUK Task Group chaired by Sir William Wakeham*, UUK and RCUK, June.

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