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Assessing innovation spillovers from the public science system

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Assessing innovation spillovers from the public science system

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ABSTRACT

Knowledge – embodied, explicit, and tacit - drives innovation. Research and development and other knowledge creation activities play a key role, as does the type of external knowledge sourcing central to models of open innovation. As knowledge is a semi-public or public good, however, firms may also obtain knowledge unintentionally through spillovers. Using matched data from Gateway to Research, the UK Innovation Survey and the Business Structures Database, we estimate the innovation spillovers from the UK public science system on other non-participating firms. Our findings emphasise the importance of localised horizontal (intra-industry) spillovers in fostering the adoption of process and product innovations, while localised vertical (inter-industry) spillovers have their strongest effects on the development of new patents. University spillovers prove weak, although there is some evidence of a positive effect on patenting in high-tech and larger firms, and on new-to-the-market innovation in low-tech firms. Looking at more specific industry and spatial patterns suggest spillovers from publicly funded R&D projects are strongest in the machinery, electrical equipment, transport equipment and chemicals manufacturing industries as well as in professional services (B2B), ICT and financial services. Spatially, horizontal spillovers effects prove strongest in some rather specific localities, perhaps reflecting an element of industrial clustering, while vertical (inter-industry) effects prove more significant across a wider range of areas.

Keywords: Innovation; university-industry; knowledge spillover; public R&D.

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1. INTRODUCTION

Knowledge – embodied, explicit, and tacit - drives innovation. Understanding the mechanisms through which firms create or acquire the knowledge necessary to innovate is therefore critical to understanding innovation itself. Research and development – and other knowledge creation activities – play a key role, as does the type of external knowledge sourcing central to models of open innovation (Torchia and Calabro 2019; Ramirez and Garcia-Penalvo 2018). Firms may also obtain knowledge vicariously or unintentionally, however, through spillover mechanisms such as social contacts between employees and those in other firms, media publicity or demonstration effects, or through the mobility of labour between enterprises (Roper and Love 2018).

Spillovers - un-priced, and unintentional, knowledge externalities – occur because knowledge can act as a semi-public or public good (Sadri 2011). As a result, knowledge can be 'promiscuous: even with a well-designed intellectual property system. The benefits of new ideas are difficult to monetise in full' (Bloom, Van Reenen and Williams 2019). So, firms investing in R&D or innovation may derive private benefits in terms of increased sales and/or productivity, but will also involuntarily generate spillovers with potential benefits for other firms' innovation. R&D undertaken by universities or other research organisations may also generate similar knowledge spillover effects boosting firms' innovation (D'Este et al., 2013).

Here, we focus on local innovation spillovers which originate from publicly funded R&D and innovation projects undertaken in UK firms, universities and other not-for-profit organizations and which benefit firms who are non-recipients of public R&D or innovation support[1]. Our analysis uses data from the Gateway to Research database which provides information on all R&D and innovation projects publicly funded through the UK Research Councils over the 2004-16 period. This is matched with longitudinal performance data from the Business Structure Database and detailed innovation data from the UK Innovation Survey. We believe this is the first comprehensive analysis of innovation spillovers from

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[1] See Vanino et al. (2019) for a study of the direct effects of UK publicly funded R&D and innovation projects on participating firms and Zhang et al (2019) for an investigation of the effects of Triple Helix interactions between research institutes, industries and universities on the participants' scientific performance. For a recent (meta-) analysis of R&D spillovers as a source of productivity gains, see Ugur et al. (2019).

UK Research Council grants to the rest of the economy. Our analysis makes three main contributions to the existing literature. First, we examine which types of innovative activity benefit most from localised university-to-business (U2B) and business-to-business (B2B) spillovers. This extends the limited existing literature on the role of spillovers in driving new-to-the-market *innovation* and new-to-the-firm *imitation* (Cappelli et al., 2014). Second, we consider which types of firms not engaged with the public science system benefit most from spillovers from publicly funded R&D, distinguishing spillover benefits for smaller companies and for firms with stronger capabilities to take advantage of external knowledge (Andrews et al., 2015). Thirdly, in an extension to our main analysis, we consider the strength of spillovers in specific UK industries and localities.

Taking into consideration different sources of knowledge spillovers, our findings highlight the importance of localised horizontal (intra-industry) spillovers in fostering the adoption of new process and product innovations, while localised vertical (inter-industry) spillovers have their strongest effects on the development of new patents. University spillovers to firms outside the public science system prove weak, although there is some evidence of a positive effect on patenting in high-tech and larger firms, and for new-to-the-market innovation in low-tech firms. Looking at more specific industry and spatial patterns suggest spillovers from publicly funded R&D and innovation projects are strongest in the machinery, electrical equipment, transport equipment and chemicals manufacturing industries as well as in professional services (B2B), ICT and financial services. Spatially, horizontal spillovers effects prove strongest in some rather specific localities, perhaps reflecting an element of industrial clustering, while vertical effects prove more significant across a wider range of areas.

We develop the argument as follows. Section 2 provides a brief overview of existing evidence on spillovers from R&D and innovation drawing primarily on recent econometric studies. Section 3 develops hypotheses related to the links between spillovers, imitation and innovation and firms' encoding capacity. Section 4 describes our data and analytical approach. Section 5 summarises and discusses the key findings and Section 6 extends the analysis to industry sectors and specific localities. Section 7 concludes.

2. LITERATURE REVIEW

Due to the public good characteristics of knowledge, private returns to R&D tend to be lower than the public or social returns (Bloom et al. 2013). The presence of these so-called 'positive externalities' or 'knowledge spillovers' are also the key reason that justifies the use of public funds to support private innovation efforts. Hence, evidence on the presence of R&D spillovers is crucial for any policy initiative seeking to maximise the social returns to R&D when using public money to do so. Knowledge spillovers may materialise in a number of ways, but usually depend on spatial and technological proximity as well as the 'absorptive capacity' of firms (Bloom et al. 2013; Lychagin et al. 2016), in terms of firms' ability to make use of external knowledge.

The econometric evidence on innovation spillovers has developed significantly over recent years. In most cases analyses are based on a relatively straightforward augmented knowledge (or innovation) production function which relates innovation at firm or regional level to a range of firm-level and spillover variables. The central idea in this type of model is that spillovers from the R&D activity of other businesses and universities can raise a firm's level of innovation above that which would be achievable from the firm's own internal resources or collaborations. In these models the innovation indicators are typically derived either from surveys such as the EU Community Innovation Survey (Cappelli et al., 2014) or measure firms' or regions' patenting activity (Furkova 2019). Spillover terms are generally defined as spatial or sectoral aggregates suggesting that firms in the same location (or sector) have access to the same spillovers.

Perhaps the most consistent finding from this literature is that R&D and innovation spillovers are generally positive whether measured at the firm (Lee et al., 2017; Segarra-Blasco et al., 2018), regional (Furkova 2019; Rodriguez-Pose and Crescenzi 2008; Funke and Niebuhr 2005), or sectoral level (Lee et al., 2017). Focussing on regional patent measures and using data for EU regions over the 2008 to 2012 period, Furkova (2019), for example, identifies significant inter-regional spillovers. Lee et al., (2017) find evidence of positive intra (horizontal) but also inter-industry spillovers. There is perhaps weaker evidence on inter-sectoral or vertical spillovers. For instance, evidence for China suggests the importance of spillovers from the R&D activities of foreign firms within the industry in which they are operating, but no evidence of inter-sectoral spillovers (Todo et al., 2011). Using data for Spain, Segarra-Blasco et al. (2018) find positive spillovers from R&D

neighbours in similar sectors (intra-sectoral) but evidence of negative spillovers in other sectors (inter-sectoral)[2].

The geographical scope of R&D and innovation spillovers and the importance of proximity has also received considerable attention. The richness of knowledge in any locality and the density of local knowledge networks or 'buzz' will shape the potential for firms to benefit from localised knowledge spillovers (Breschi and Lissoni, 2009; Ibrahim et al., 2009; Storper and Venables, 2004)[3]. As He and Wong (2012) suggest: 'local knowledge is … a semi-public good that is spatially bounded … local knowledge exchange is prompt or spontaneous because local firms are assumed to be more willing to share knowledge and exchange ideas with other local actors as a result of shared norms, values, and other formal and informal institutions that hold down misunderstanding and opportunism' (He and Wong, 2012, p. 542).

Localised knowledge may also have other spatially distinct characteristics, reflecting the presence of specific institutions (typically universities, research labs), clusters of industrial activity[4], and/or concentrations of specific types of human capital. The character of these institutions may lead to very different subject or quality profiles of local knowledge with potentially significant implications for the profile of local innovation (Cannarella, 2011). Tassey (2005), for example, argues that knowledge created by firms' research labs, government labs and universities may have some of the attributes of a quasi-public good.[5] Local mediation of such knowledge may then occur through social interaction, inter-personal networks, or through firms' links with knowledge creators or brokers such as consultants or intermediary institutions. A related literature suggests that there is a strong geographical dimension to university spillovers with evidence of significant spatial decay (Audretsch and Feldman, 1996; Anselin et al., 2000; 1997).

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[2] This type of finding is consistent with recent OECD analysis which suggests the importance of technology diffusion from frontier firms (Andrews et al., 2015).

[3] The strength of knowledge spillovers can also be affected by labour mobility, and this too has a spatial dimension (Almeida and Kogut, 1999; Breschi and Lissoni, 2009).

[4] Speldekamp et al (2020) provide a recent analysis of local clusters' potential to strengthen firm innovation.

[5] Koch and Simmler (2020) provide recent evidence of substantial local knowledge spillovers from public R&D.

Localised knowledge spillovers are generally envisaged as having positive innovation effects which generates competition effects, which are more ambiguous in terms of their impact on other local firms' innovation (Bloom et al. 2013). Positive competition effects may arise due to the competitive pressure created by local innovators and the incentives for other local firms to increase their investment in innovation inputs or expand their own collaborative networks (Aghion and Griffith, 2005; Aghion et al., 2009; Leibenstein, 1966; Vickers, 1995). Negative - market stealing effects – may also arise, however, where firms envisage lower future returns to investment in innovation due to innovation by other local firms. Evidence on the potential for both positive and negative localised R&D spillovers comes from Segarra-Blasco et al. (2018) who find positive spillovers from R&D neighbours in similar sectors in Spain but evidence of negative spillovers from R&D neighbours in other sectors.[6]

The spatial boundedness of spillovers has also been considered in the context of university spillovers with widespread evidence of a distance-decay effect from numerous countries, e.g. for Italy (Cardamone, 2018), Spain (Segarra-Blasco et al., 2018), Japan (pre-1997) (Fukugawa, 2017), Turkey (Kaygalak and Reid, 2016), the US (Lin, 2015), Australia (Bakhtiari and Breunig, 2018,the UK (D'Este et al., 2013) and Great Britain (Abramovsky et al., 2011). Caloghirou et al. (2021) find that firms' knowledge stocks play a moderating role in the relationship between industry-university collaborations and product innovation, suggesting that firms with low levels of knowledge stocks benefit more in terms of innovation from the development of knowledge flows with universities, especially in industries characterized by knowledge proximity with universities and regions with social trust. The nature of university spillovers may also depend on the type of university. Barra et al. (2019), for example, find somewhat contradictory results with positive relationships between high quality publications and product innovation, but negative links to process change in European manufacturing. Proximity to the technological frontier may also influence firms' ability to appropriate spillover benefits. Pfister et al. (2021) find positive effects of applied research conducted in universities of applied sciences on regional innovation in Switzerland. Spillovers may, however, be more important in smaller firms than

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[6] See Granstrand and Holgersson (2020) for a conceptualisation and new definition of 'innovation eco-system'. Good et al (2020) review the literature on the technology transfer eco-system, pointing out the great challenges involved with transferring science from universities to the market.

larger companies (Acs et al., 1994) reflecting other evidence of the greater importance of innovation collaboration for small firms' innovation (Vahter et al., 2014).

3. HYPOTHESES

3.1 Innovation v imitation

There is limited evidence on spillovers' contribution to innovation versus imitation (Im and Shon, 2019). New to the market innovation has very different knowledge requirements to new to the firm imitations and involves very different risks and rewards. Innovation can create first mover advantage for the innovator leading to higher returns and allowing the innovator to gain advantages in terms of market intelligence (Kopel and Loffler, 2008; Ulhoi, 2012). Imitators may copy or reverse engineer the products of an innovator or by observing market reaction to new innovations may reduce commercial risks (Astebro and Michela, 2005). Imitation offers 'second mover advantages' of reduced uncertainty albeit balanced by the likelihood of lower margins, a strategy which may be more profitable in less dynamic markets (Lieberman and Asaba, 2006). The consequences of innovation and imitation go well beyond the impact on the innovator, however. Where innovation dominates a market-place or industry this may generate a process of creative destruction with implications for technical progress, value creation by innovators and value destruction in incumbents (Roper and Hewitt-Dundas, 2017). Where imitation dominates, there may be a reduction in the variety of products or services within a market, increasing the collective vulnerability to external competition (Lieberman and Asaba, 2006). Imitation may, however, also help to maximise the social and consumer benefits of the original innovation by making products or services available to more consumers.

Firms' orientation towards innovation or imitation will shape their involvement in knowledge creation and acquisition from external partners (Schmidt, 2010). Decisions about investments in knowledge creation – through in-house R&D for example – will also have implications for firms' ability to identify and absorb useful external knowledge (Cohen and Levinthal, 1989). We might expect firms emphasising an innovation-based strategy to emphasise both knowledge creation and engagement with a broader group of external partners. Engaging with more external partners increases the probability of obtaining useful external knowledge that can be combined with the firm's internal knowledge to produce innovation (Leiponen and Helfat, 2010). The extent of a firm's innovation linkages may also have significant network benefits, reducing the risk of "lock-in" (Boschma, 2005). Tradeoffs are evident here, however, with the potential for ‘over-search’ and negative returns to adding additional partners when firms network of external partners is large (Laursen and Salter, 2006; Leiponen and Helfat, 2010; Grimpe and Sofka, 2009; Garriga et al., 2013). Small firms’ more limited managerial and cognitive capacity may also mean that the optimal number of innovation partners is lower than that for larger firms[7].

Firms emphasising innovation and imitation will also seek different types of external knowledge (Roper et al., 2016) and may therefore experience different benefits from incoming spillovers. Firms with an orientation towards imitation will prioritise non-interactive learning focussing on the acquisition of codified knowledge through reverse-engineering, attendance at fairs, seminars, congresses and workshops, reading of literature and patents etc. An innovation orientation may require a stronger focus on newer, tacit knowledge either not yet codified or treated as proprietary by its inventors (Roper and Love, 2018). This is consistent with the limited evidence which exists on spillovers’ contribution to innovation and imitation. Using data from the German Community Innovation Survey, Cappelli et al. (2014) find that spillovers from technologically-proximate competitors have the strongest impact on imitation; spillovers from customers, suppliers and universities have instead stronger innovation effects. This suggests:

Hypothesis 1: Innovation and imitation effects

H1a: Localised spillovers from R&D and innovation by firms engaging in publicly-funded R&D and innovation projects will have the strongest positive effect on imitation by non-participating firms.

H1b: Localised spillovers from R&D by universities engaging in publicly-funded R&D and innovation projects will have the strongest positive effect on innovation by non-participating firms.

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[7] Vahter et al (2014), for example, find that for small firms (with less than 50 employees) this point is reached when firms have four to five types of external linkage while for larger firms the turning point is not reached until at least 8-9 linkage types.

3.2 Encoding capacity

Firms' ability to search for and use external knowledge for innovation – absorptive capacity - has been widely discussed since the seminal work of Cohen and Levinthal (1989). In terms of firms' ability to capture external knowledge from spillovers, however, it is firms' assimilation or 'encoding' capacity which is important rather than firms' search capacity. Encoding capacity reflects firms' ability to make effective use of incoming knowledge for innovation, and encoding capacity will therefore play a moderating role in the relationship between any given level of external knowledge and marketable innovation (Roper and Love, 2017). Encoding capacity itself is likely to be determined by a range of factors related to organisational culture, structure and resources. Organisations with more 'open' cultures which enable creativity and knowledge sharing will also facilitate encoding capacity. More closed or rigid cultures may make this more difficult (Lucas and Goh, 2009). Attitudinal differences, such as a 'not-invented-here' syndrome, may also create barriers to encoding (Agrawal et al., 2010). Other factors related to organisational structure may also play a functional role in shaping encoding capacity. The number of individuals with boundary-spanning roles, for example, may shape firms' ability to share knowledge effectively within the firm and their encoding capacity (Johri and Ieee, 2008). Firms' use of development teams may help to distribute and apply knowledge effectively maximising encoding capabilities (Ernst et al., 2010; Love and Roper, 2009; Atuahene-Gima and Evangelista, 2000).

These factors mean that encoding capacity may vary significantly between firms, creating differences in firms' ability to encode different types of incoming knowledge into innovation (Schmidt, 2010). Smaller firms with more limited internal resources may, for example, have on average lower encoding capacity than larger firms (van de Vrande et al., 2009). Similarly, performance differences like higher productivity or growth may be indicative of stronger managerial competences and may suggest higher levels of encoding capacity. This suggests:

Hypothesis 2: Encoding capacity

H2: Localised spillover effects from publicly-funded R&D and innovation projects on both innovation and imitation by non-participating firms will be stronger where these firms have greater encoding capacity.

4. DATA AND METHODS

4.1. Policy context

Our analysis covers the period 2006 to 2016, a period encompassing the great recession, and during which there were important changes in the UK's innovation and industrial policy landscape (Hildreth and Bailey, 2013). These changes differed in each of the different nations of the UK. In England, Regional Development Agencies (RDAs) were abolished in 2010-12 and replaced with more localised, business-led, Local Enterprise Partnerships or LEPs (Pike et al., 2018). The profile of regional innovation supports provided by the English RDAs varied by region, but typically included Innovation Vouchers, proof-of-concept funding and support for commercialisation through schemes such as Grants for R&D (subsequently renamed 'Smart'). The closure of the RDAs led to the centralisation of innovation support schemes under the control of the Technology Strategy Board (TSB) which was later renamed Innovate UK. After 2010, partly as a consequence of the closure of the RDAs, the number of R&D grants provided by TSB/Innovate UK rose rapidly with an increasing focus on smaller firms (Figure 1). In 2014-15, Innovate UK funded 1,401 projects of which around 51 per cent involved university-industry collaboration (Technology Strategy Board, 2015). At the end of our analysis period (2016), Innovate UK simplified its scheme portfolio focusing the majority of support through a series of sectoral competitions for grant funding (Innovate UK, 2016). Grants for R&D and innovation from Innovate UK are available to firms in England, Scotland, Wales and Northern Ireland. However, in Scotland, Wales and Northern Ireland additional support for R&D and innovation is also available to local firms from their respective regional development agencies[8].

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[8] For example, see https://www.investni.com/support-for-business/funding-for-innovation-and-research-and-development. Accessed: 29th March 2020.

While the business-facing elements of UK innovation policy changed significantly during our study period, there was more stability in public funding for university-based R&D and collaborative R&D between universities and firms. Before 2016, the UK had seven independent Research Councils organised broadly along disciplinary lines[9]. The most significant Research Council in terms of its business impacts was the Engineering and Physical Sciences Research Council (EPSRC) (Scandura, 2016)[10]. EPSRC research projects are typically university-led, often involve business collaborators, and are awarded on a competitive basis. EPSRC funding is provided only to university partners, with business partners either making financial or in-kind contributions to a project (e.g. equipment use or staff time)[11]. Funded projects cover most industries, although there is a concentration in high-tech manufacturing and knowledge intensive services (Figure 2) and in some more central regions of the UK (Figure 3). Evidence of the impact of EPSRC support on participating firms is relatively limited although Scandura (2016) provides evidence of input additionality in terms of both R&D expenditure and employment in participating firms two years after the end of EPSRC projects. More recently Vanino et al. (2019) also provide evidence of substantial business growth effects on participating firms from a range of UK Research Council projects.

4.2. Data

To model knowledge spillovers from publicly supported R&D and innovation in the UK we match data from three datasets. First, Gateway to Research (GtR) provides data on all projects funded by the UK Research Councils and Innovate UK over the 2006 to 2016 period, including data from Innovate UK, the seven Research Councils and the National Centre for the Replacement, Refinement and Reduction of Animals in Research (NC3Rs)[12].

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[9] That is the Arts and Humanities Research Council (AHRC), the Biotechnology and Biological Sciences Research Council (BBSRC), the Economic and Social Research Council (ESRC), the Engineering and Physical Sciences Research Council (EPSRC), the Medical Research Council (MRC), the Natural Environment Research Council (NERC).

[10] During the period we consider here the EPSRC and the other UK Research Councils provided research funding through a wide range of schemes. The main interventions were research grants and university-industry (U-I) research collaborations along with training grants, fellowships, innovation vouchers and support for collaborative R&D projects.

[11] Innovate UK projects aimed at the commercialisation of innovation operate differently, with much of the funding going to private companies across several industries and regions, inside and outside of the UK.

[12] We abstracted the data for this study between the 2nd and the 5th of January 2017 from the Gateway to Research website available at the following link: http://gtr.rcuk.ac.uk. For more

For the current analysis we use data from the GtR as the source of potential spillovers. Second, the ONS Business Structure Database (BSD) covers the whole population of businesses in the UK between 1997 and 2016 (ONS, 2017) and provides information on firms' age, ownership, turnover, employment, industrial classification at the SIC 4-digit level and postcode[13]. Data from the BSD is used here to structure the analysis and provide a number of control variables. Finally, we use data from the UK Innovation Survey (UKIS) to define a range of innovation output measures used as dependent variables. The UKIS is conducted every two years by means of a postal questionnaire and extensive telephone follow-up survey (ONS, 2018). The UKIS is based upon a core questionnaire developed by the European Commission (Eurostat) and Member States, and forms part of a wider survey covering European countries – the European Union Community Innovation Survey or CIS.[14] Information in the Annex provides a fuller description of each of the individual datasets.

Data access and matching was undertaken through the ESRC UK Secure Data Service. The data matching process involved a number of steps:

- Step 1 – GtR provides company name and address details and for around 80 per cent of firms the Company Reference Number (CRN). For the remaining firms we manually added a CRN using the Bureau Van Dijk FAME database and the Company House data based on company names. Postcodes were used to distinguish between multiple firms with the same name.
- Step 2 – GtR provides the names of around 34,000 organisations which participated in R&D grants funded by the Research Councils. Around 40 per cent of these organisations were firms and a proportion of organisations were international. A significant proportion of the remainder were UK universities. Based on the organisation name and some internet research we categorised each organisation

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information regarding the GtR data and data management process please refer to Vanino et al. (2019).

[13] The annual BSD dataset is a live register of data based on the annual abstracts from the Inter-Departmental Business Register (IDBR) and collected by HM Revenue and Customs via VAT and Pay As You Earn (PAYE) records covering the population of firms operating in the UK.

[14] The background and motivation for the innovation survey can be found in the Organisation for Economic Co-operation and Development's (OECD) Oslo manual (OECD, 2005), along with a description of the type of questions and definitions used. In the UK, the Office for National Statistics (ONS) – the UK official government statistical office – manages the administration and data collection for the UKIS.

into one of 3 macro categories: firms, universities and public research institutes, and other organisations.[15]

- Step 3 – GtR data – with the added CRNs and organisational type – was imported into the ONS Secure Data Lab and CRNs were matched with the anonymised enterprise reference numbers (or ENTREF). This resulted in an anonymised version of the GtR dataset including the ENTREF field which could then be matched to BSD and the UKIS.
- Step 4 – Using UKIS data as the starting point GtR and BSD data were matched in using ENTREFs. This created an enriched unbalanced panel database at the firm-level reflecting the structure of the UKIS survey data.

This process also allowed us to identify firms included in the UKIS which had participated in publicly funded research projects (i.e. also appeared in the GtR dataset). These observations were excluded from the analysis which therefore focuses purely on the indirect spillover effects of research grants on the innovative performance of private firms which have not themselves participated in publicly funded research projects.

4.3. Dependent variables

Our dependent variables are all derived from the UK Innovation Survey and are intended to capture different aspects of firms' innovation activity. Two of our indicators relate to the type of innovation firms might have undertaken: product/service innovation or process innovation. A third indicator relates to whether firms applied for any patents during the three years prior to the date of the survey. Each of these indicators are binary variables taking value 1 if the firm undertook a particular type of innovation activity in the two years prior to the date of the survey and 0 otherwise. Note, however, that patent holdings differ significantly between sectors with service sector firms typically less likely than manufacturing firms to patent new service offerings (Morikawa 2019). This may have implications for both the scale of spillovers for this variable and their likely effects. Finally, we include two indicators which relate to the novelty of the innovation which firms

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[15] The category "other organisations" include schools, hospitals, government authorities, charities, cultural organisations, academic journals, associations, funds, membership organisations and federations.

introduced, and whether these were new to the market (*innovation*) or new to the firm (*imitation*). In these two cases, the indicators represent the share of total sales related to new-to-market and to new-to-business product or service innovations adopted in the past three years, i.e. commercialised research outputs[16].

4.4. Spillover Measures

Following the literature previously reviewed, we identify four different channels through which knowledge could spillover from publicly funded R&D and innovation projects to non-participating firms. First, following the Marshallian theory of agglomeration (Glaeser et al., 1992), knowledge spillovers could be horizontal, where firms producing similar products and competing in the same local market benefit from each-others R&D activities. To capture this effect, we build a measure of horizontal spillover $HOR.IND_{rst}$ calculated as the value of public R&D funds received by all firms (i, i=1,…n) participating in innovation projects within the same SIC2 industry (s) and LEP-NUTS2 region (r) (Ornaghi, 2006):

$$HOR.IND_{rst} = \sum_{i=1}^{n} GtR_{irst}$$

Second, technological proximity may facilitate knowledge spillovers if firms sharing technologically related production processes are able to better absorb external knowledge and therefore take advantage of knowledge created for related production functions (Bloom et al., 2013). To capture this effect we build a second measure of knowledge spillovers considering the value of public R&D and innovation funding received by firms in vertically integrated industries located within the same LEP-NUTS2 region $VERT.IND_{rst}$. We follow Javorcik (2004) to derive our vertical spillover measure, using the average intermediate demand-supply linkage between SIC2 industry pairs, based on the 2005 UK input-output tables, to provide a measure of the linkages between all sector pairs in the UK (α_{sp}). Then, for each sector *(s)* we construct the measure of publicly funded R&D vertical spillovers by weighting the value of public funds received by all participating firms in innovation projects in SIC2 sector (*p*) and LEP-NUTS2 region (*r*) $\left(GtR_{rpt}\right)$ by the relative measure of vertical

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[16] See Belitski et al. (2019) for a demonstration that research commercialization is associated with the direct industrial funding of university research.

integration between each pair of sector (α_{sp}), and averaging across vertically integrated sectors (p, p=1,…,P) within each region:

$$VERT.IND_{rst} = \frac{1}{P}\sum_{p=1}^{P} \alpha_{sp} \times GtR_{rpt}$$

In this way we are able to comprehensively estimate the spillovers from publicly funded R&D projects, not only considering those firms operating within the same region and industry, but also the externalities spreading throughout vertically integrated industries within the same region.

Finally, we also consider the potential localised spillovers for private firms originating from publicly funded research in universities and other organisations. In particular universities and public research institutes could be the source of cutting-edge knowledge that only once integrated with private resources and capabilities could result in commercially exploitable innovations (Murray et al. 2016). Thus, we build two other measures of knowledge spillover: the first is based on the value of funds received by universities and other public research institutes (*u*) to participate in publicly-funded R&D and innovation projects within the same LEP-NUTS2 region (*r*) $UNI.SPILL_{rt}$. The second measure considers the value of R&D funds received by third sector organisations (schools, charities, hospitals, etc.) (*o*) supported by publicly-funded R&D and innovation projects within the same LEP-NUTS2 region (*r*) $OTH.SPILL_{rt}$:

$$UNI.SPILL_{rt} = \sum_{u=1}^{U} GtR_{urt}$$

$$OTH.SPILL_{rt} = \sum_{o=1}^{O} GtR_{ort}$$

4.5. Econometric Methodology

Our econometric approach estimates the impact of knowledge spillovers originating from participants in publicly funded research projects on the innovative performance of non-participating private firms. We estimate the following econometric model:

$$\begin{aligned} Y_{krst} \\ &= \beta_0 + \beta_1 HOR.IND_{rst-1} + \beta_2 VER.IND_{rst-1} + \beta_3 UNI.SPILL_{rt-1} + \beta_4 OTH.SPILL_{rt-1} \\ &+ \beta_5 X_{kt} + \gamma_k + \gamma_t + \gamma_{rt} + \gamma_{st} + \varepsilon_{kt} \end{aligned}$$

Where Y_{kt} measures firm k's innovative performance in period t, $HOR.IND_{rst-1}$ and $VER.IND_{rst-1}$ are our measures of horizontal and vertical industrial spillovers at the industry s and region r level. $UNI.SPILL_{rt-1}$ is our measure of university spillovers and $OTH.SPILL_{rt-1}$ is our measure of spillovers from other kind of organisations publicly funded for their R&D activities within the same region r. X_{kt} includes a series of firm-level control variables following previous studies modelling knowledge production functions, including internal R&D capabilities, measured as the total investment in R&D activities; total employment; labour productivity (turnover per employee); foreign ownership; firm internationalization (export intensity); and the stock of patents. Summary statistics for the variables included in the model are reported in Table 1, while the correlation matrix table is available in the Annex in Table A1. For each model we also include firm (γ_k) and wave (γ_t) fixed effects, and SIC2 industry (γ_{st}) and LEP-NUTS2 region (γ_{rt}) time trends, and we estimate clustered robust standard errors at the region-industry level. We first estimate baseline models for all firms, but also report sub-sample estimates designed to explore whether spillovers vary between knowledge intensive and low-tech sectors, by firms' size and by spatial location.

5. RESULTS

Estimates of the innovation production function including the four spillovers variables for all firms are reported in Table 2. We report five models of the effect of spillovers on the probability of process and product innovation, imitation – or new to the firm product or service changes, innovation – or new to the market product or service changes - and the probability that the firm applied for patents. Following Hypothesis 1a, we anticipate that business to business spillovers will have their strongest effects on imitation. We find no support for this hypothesis. Instead, horizontal (i.e. intra-industry) localised spillovers are linked to both process innovation and the introduction of new to the market products, although the magnitude of the effects is relatively small. The link between horizontal spillovers and process innovation in other firms could be linked to the sharing or demonstration of new production technologies developed thanks to public R&D funding across agglomerated firms, especially when belonging to the same industrial cluster. The somewhat larger link between horizontal spillovers and innovation – i.e. new to the market products or services – indicates that a 1 per cent rise in public R&D funding allocated to nearby firms operating within the same sector increases the sales related to new-to-market innovations of firms not participating in government funded R&D projects, i.e. the amount of successfully commercialised new-to-market product or service innovations, by around 0.04 per cent. The small magnitude of this spillover effect is in line with previous evidence on R&D externalities (Bloom et al., 2013; Lychagin et al., 2016), and it is an additional effect on innovation outcomes on top of the typically stronger effect of a firm's internal R&D investment on its innovation output, and the direct effect of the public R&D funding on the innovativeness of firms which were participating in publicly supported R&D projects. As a back of the envelope calculation, in the period of analysis (2006-2016) there were on average 230,000 firms operating in the UK with more than 10 employees, after removing directly GtR supported firms, with an average turnover of £14,230,000. From the UKIS we know that around 8.2% of firms report turnover due to new-to-market innovation in the same period, around 19,000 firms of the total sample. Our estimations suggest that a 1 standard deviation increase in horizontal spillovers would increase the share of turnover coming from new-to-market innovation by 0.20%, so by around £28,580. Thus, the overall effect of the horizontal spillover on the economy would be an increase in the turnover coming from innovative products and services for non-supported firms by almost £540 million per year. In addition, horizontal business-to-business spillovers have also weak positive but statistically insignificant effects on the other innovation metrics.

Vertical (inter-industry) spillovers originating from publicly-funded R&D activities in proximate and vertically integrated firms only have a small effect on the probability of patenting by the spillovers-receiving firms. This evidence might highlight the relevance of the exchange of diverse and tacit knowledge to foster patents. This could be particularly important in order to integrate new external knowledge, which is distant from the traditional core activities of the firm, with internal capabilities in order to create advanced and disruptive innovations that are worth being patented.

It is notable that we find no significant spillovers from publicly funded research projects in local universities or other third organisations on the cohort of innovative firms not participating in publicly funded research activities. This finding could be related to the trade-off between public and private R&D, where the objectives of public research institutions may diverge from those of private firms in terms of appropriability, knowledge dissemination and the time-horizon for any given project (Robin and Schubert, 2013). For these reasons, spillovers from publicly funded R&D projects in universities and in the third sector might not be directly relevant for the primary goal of firms, which is the commercialization of innovations.

Taken together these results provide little support for either Hypothesis 1a or 1b. Contrary to expectations, business-to-business spillovers prove most important for process and more radical innovation outcomes.

Hypothesis 2 relates to the positive anticipated effects of encoding capacity on firms' ability to capture the benefits of knowledge spillovers. Larger firms are likely to have stronger encoding capacities as are those in high-tech or knowledge intensive sectors. To test Hypothesis 2 we therefore investigate the differential impact of spillovers on small firms (with less than 50 employees) and medium-large firms with more than 50 employees in Table 3, and those in low and high-tech sectors in Table 4. In terms of firm size, we find little consistent evidence that spillover effects are stronger in larger firms. Indeed, for smaller firms we find that the positive effect of horizontal spillovers is significant for both process and product innovations and, as in the whole sample, a firm's sales due to innovative products.

Regarding vertical externalities in medium and large firms, we find a relatively similar pattern to that for horizontal spillovers with a positive and significant effect only on patenting. This effect is similar to the estimates for all firms and stronger for medium-large rather than small firms, which might not have the adequate internal resources needed to fully exploit these spillovers. Here, we also find positive, weakly significant spillovers from local university research on patenting activity but again only for medium-large firms. Previous studies have highlighted the importance of the interaction between science and industry as a channel for knowledge diffusion. However, the type of research conducted by universities tends to be closer to the technological frontier, and thus could be relevant only for more productive and larger firms (Dornbusch and Neuhuusler, 2013). As a result, such collaborations are more likely to result in the recombination of complex knowledge that is considered to be relatively far away from a firm's traditional core R&D activities, resulting in patentable innovations (Belderbos et al., 2004).

Encoding capacity may also be greater in high-tech firms and therefore we consider the effects of knowledge spillovers from publicly funded R&D projects across industries in Table 4. Again, contrary to Hypothesis 2, we find little evidence that spillovers are consistently stronger for firms in high-tech or knowledge intensive sectors. Our analysis suggests that the only significant effects of publicly funded R&D spillovers in high-tech industries are on the development of new patents through vertical externalities. This reflects our earlier finding for both larger and smaller firms in Table 3. Perhaps unsurprisingly, this effect is not evident among low-tech firms. These firms do, however, benefit from horizontal spillovers on process innovation. Here too university-to-business spillovers also prove important in increasing the share of sales related to new-to-market innovative products. Thus, and corroborating previous evidence, externalities from publicly funded R&D projects while supporting knowledge intensive firms in the recombination of complex knowledge for the development of new patents, could also help low-tech firms more distant from the technological frontier. Interestingly, overall we find that where publicly funded R&D projects result in significant spillovers from participating to non-participating firms, these are either horizontal only or vertical only, but not both.

6. EXTENSION ANALYSIS – SPATIAL AND INDUSTRY SPILLOVER EFFECTS

Our earlier analysis relates to local spillovers for relatively broad groups of firms. Here, we further investigate the industrial and regional pattern of these externalities across the UK. Guided by the most significant effects in the aggregate analysis, we focus on vertical and horizontal business-to-business spillovers and university-to-business spillovers. Marginal effects of the three main knowledge spillovers for each innovation output for specific industries are included in Figure 4. This suggests three key observations. First, the introduction of product and process innovations are mostly supported by horizontal (inter-industry) spillovers. Second, growth in sales related to new-to-market innovations seems mainly linked to spillovers from publicly funded R&D projects in vertically integrated industries. Third, the development of new patents is influenced by a mix of externalities channels across many industries, however, the marginal effects seem smaller in magnitude, in line with the lack of precision in our aggregate estimates. Across industries, and looking at the different innovation output measures, spillovers from publicly funded R&D projects are strongest in the machinery, electrical equipment, transport equipment and chemicals manufacturing industries as well as in professional services (B2B), ICT and financial services.

Finally, we explore the spatial pattern of business-to-business spillovers from publicly funded R&D across English LEPs and NUTS2 regions in Scotland, Wales and Northern Ireland in Figure 5. In each of the maps darker shades represent areas where spillover effects were strongest. Horizontal spillover effects prove strongest in some rather specific localities influencing sales of new-to-market innovations in Cambridgeshire, Sussex and the East Midlands and patents in Oxfordshire and Leicestershire, Wales, New Anglia and the South East. Vertical externalities have more geographically dispersed effects. In particular, vertical (inter-industry) foster new-to-market sales in the Greater London Authority, the East Midlands and Swindon region while patent effects are statistically significant across a number of UK localities, with particularly strong effects for firms located in the West Midlands, Lincolnshire and the South-East of Scotland.

7. CONCLUSIONS

It is clear from previous evidence that firms participating in Research Council funded R&D and innovation projects are more innovative (Scandura, 2016) and grow more rapidly (Vanino et al., 2019) than non-participants. Here, we consider the spillover effects of this funding on innovative outcomes in non-participating firms. We use administrative data from the Gateway to Research database which provides information on all publicly funded R&D projects in the UK between 2006 and 2016. We identify four main channels through which publicly funded R&D spillovers could occur, considering spillovers from local universities, industrially related and geographical proximate private companies. Our initial hypothesis suggesting that business-to-business spillovers might be stronger on imitation and university-to-business spillovers might have stronger effects on innovation proves unsupported. We also find little consistent evidence that spillovers are stronger for firms in high-tech or knowledge intensive industries. Instead, our analysis emphasises the importance of horizontal spillovers in fostering the adoption of new process and product innovations, while vertical spillovers have their strongest effects on the development of new patents (Table 4). These effects are heterogeneous across firms' characteristics and industries. In particular, horizontal spillovers are mainly relevant for the growth of sales of new-to-market innovative products for small firms, while spillovers from vertically integrated industries and from universities have a positive effect for medium-large firms on the development of new patents (Table 4). For firms in low-tech sectors there are significant horizontal spillover benefits for process innovation. One potentially surprising element of our results is the weakness of university spillovers (Table 4). These prove generally insignificant although there is some evidence of a positive effect on patenting in high-tech and larger firms and for new-to-the-market innovation in low-tech firms.

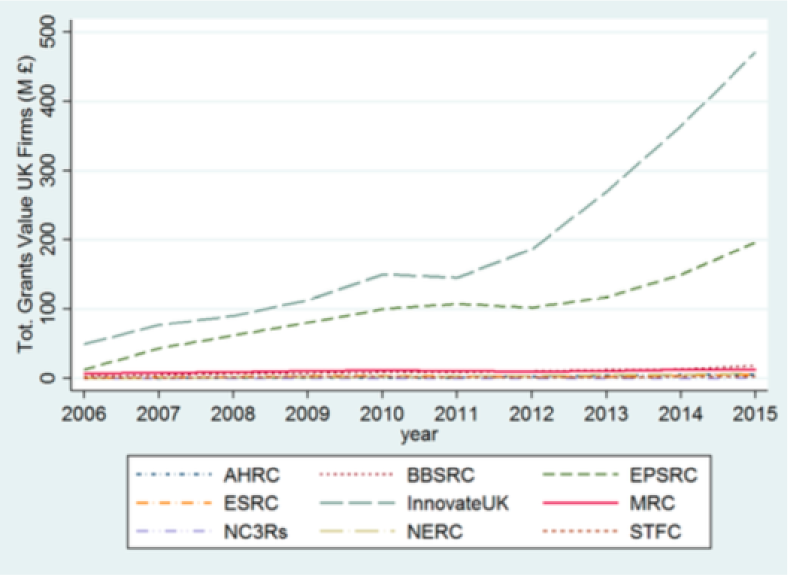
Extending our analysis to look at specific industry and spatial patterns suggest two additional conclusions. First, spillovers from publicly funded R&D projects are strongest in the machinery, electrical equipment, transport equipment and chemicals manufacturing industries as well as in professional services (B2B), ICT and financial services. Second, while horizontal spillover effects prove strongest in some rather specific localities, perhaps reflecting an element of industrial clustering, vertical (inter-industry) effects prove significant across a wider range of areas.

The weakness and relatively small size of the spillover effects we identify here is perhaps surprising. However, this may reflect our specific focus on the impact of spillovers from publicly funded projects on innovating firms which are themselves outside the publicly-funded science system. These 'outsider' firms may have lower encoding capacity than 'insider' firms, and perhaps also a focus on more incremental rather than radical innovation. It is also important to remember that although public funding on supporting R&D and innovation in the UK is significant – around £6bn pa - the proportion of innovating firms which are directly supported by publicly-funded R&D and innovation projects remains relatively small. Around 15,000 firms were supported by the UK public science system over the period of our analysis, only a tiny fraction of all UK firms with more than ten employees. Our analysis therefore captures the average spillover from this relatively small proportion of the population of publicly-supported firms – and the universities and other organisations they work with – to the very much larger group of outsider firms.

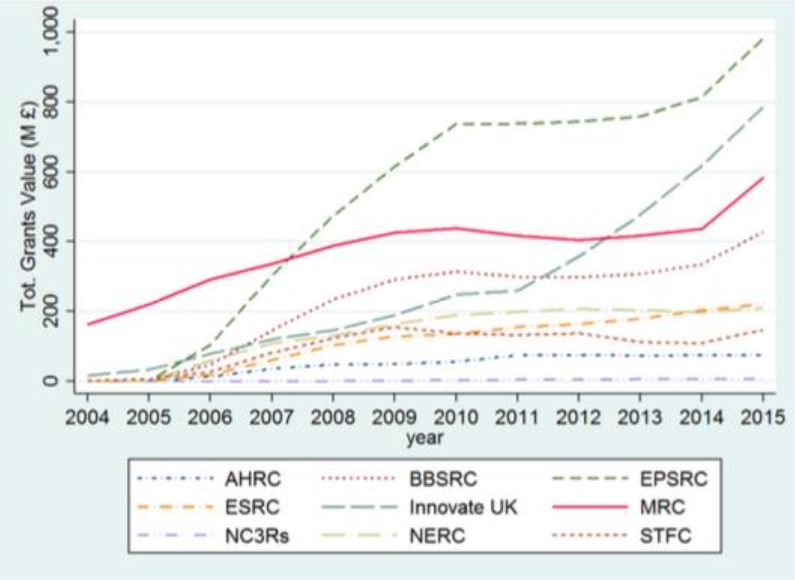
Our analysis is subject to a number of limitations. First, we might not consider the correct timing of the spillover effects, as these could take longer than 2 years to materialise. Secondly, we currently omit any consideration of R&D tax credits, which have become more important over this period in the UK. Third, although the GtR data cover the bulk of public R&D and innovation spending in UK, we still omit public support from government in the devolved territories of Scotland, NI and Wales. Finally, our findings are limited by the extent of the UKIS data, which is still based only on a surveyed sample of innovative firms. Future research is needed in order to address these issues and better understand the nature of knowledge externalities from the public science system.

Figure 1: Evolution of UK Research Council funding

(a) Total grant value (£m)

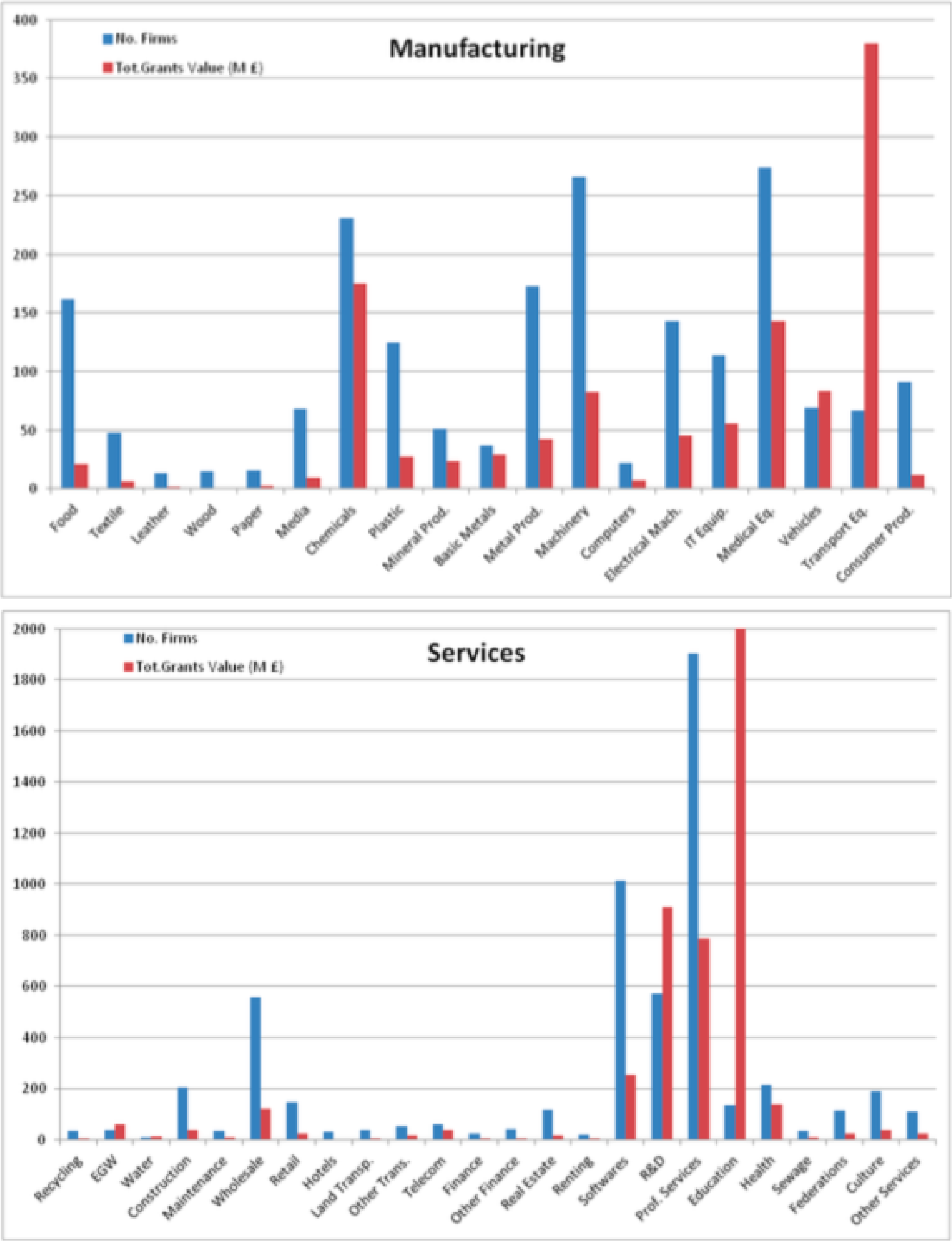


(b) Total grant value to UK firms (£m)



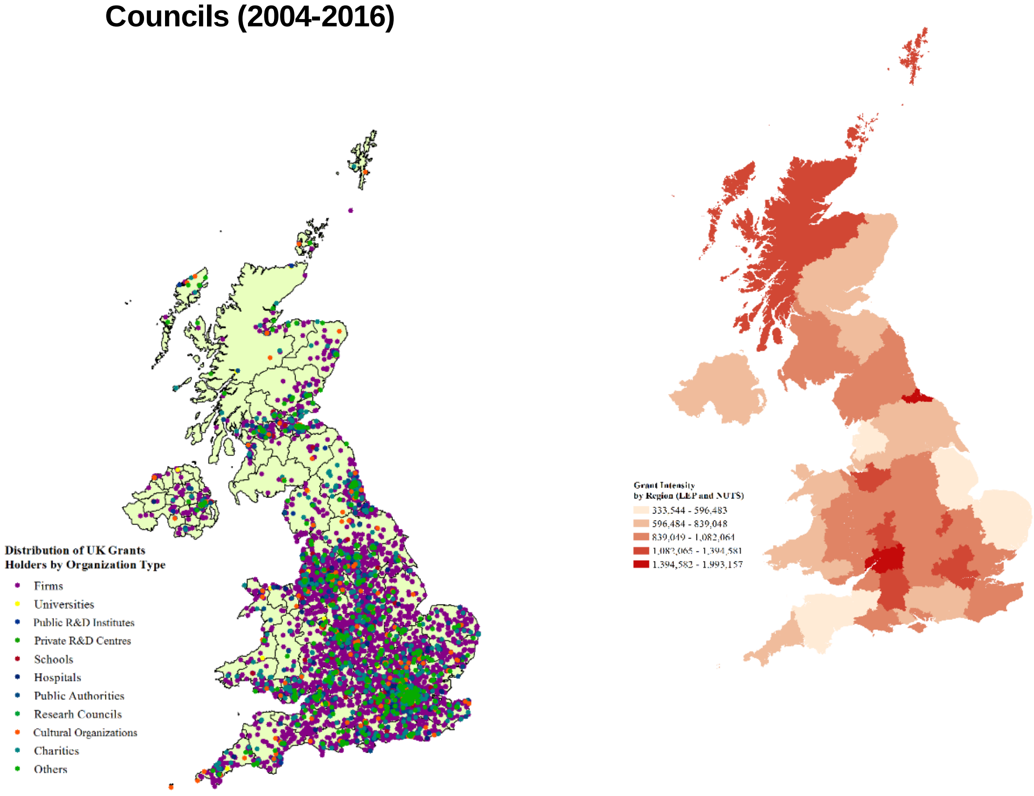
Notes: Authors' analysis of GtR data for the period 2006-2016.

Figure 2: Industrial distribution of UKRC funded firms



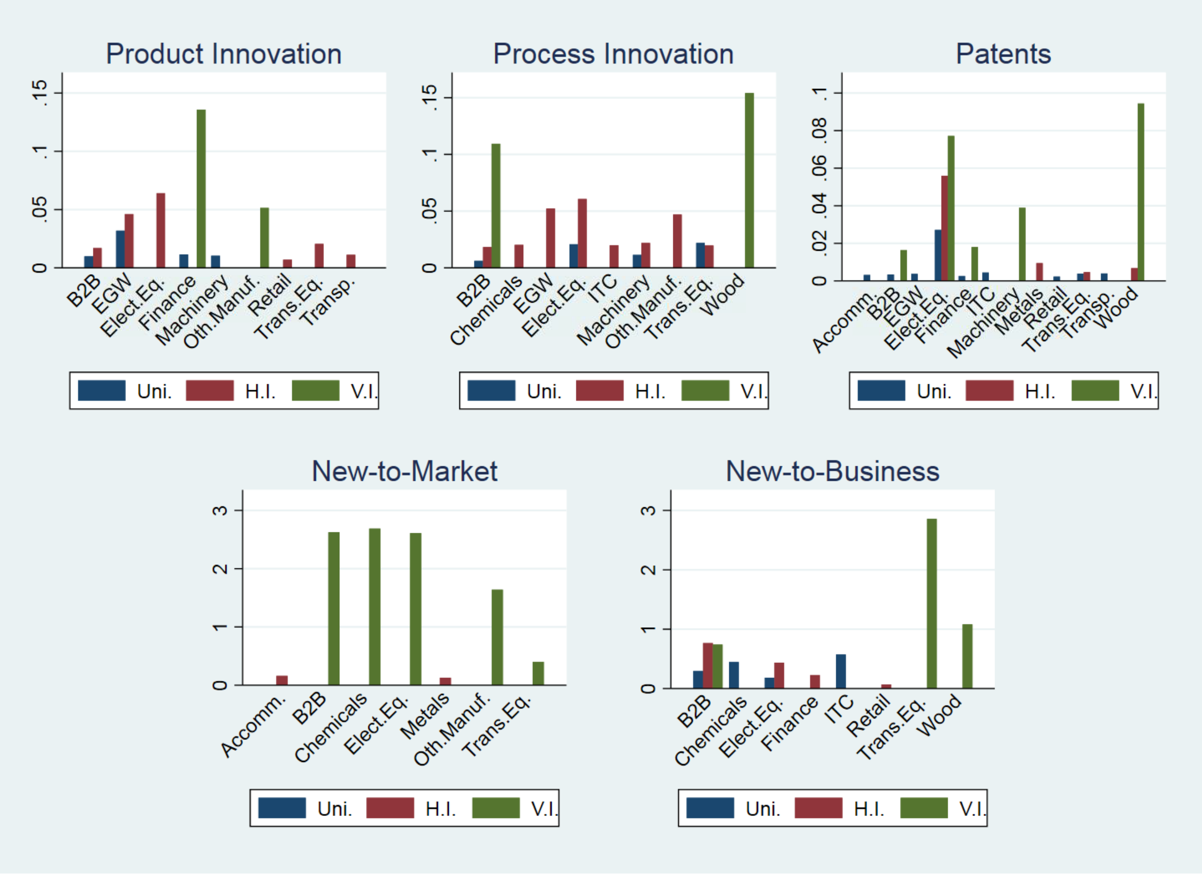
Notes: Authors' analysis of GtR data for the period 2006-2016.

Figure 3: Geographical distribution of participating organizations and intensity of the funds allocated by UK Research Councils (2004-2016)



Notes: Authors' analysis of GtR data for the period 2006-2016.

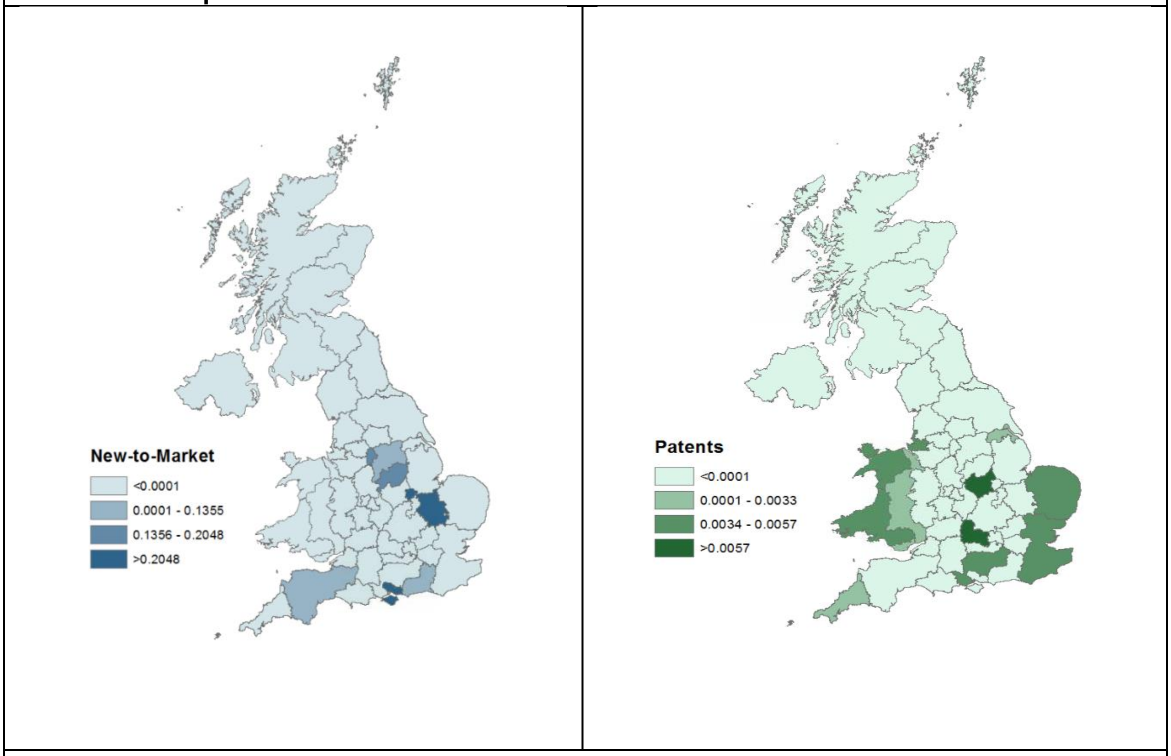
Figure 4: Effect of publicly funded R&D spillovers on firms' innovation output – Industrial distribution.



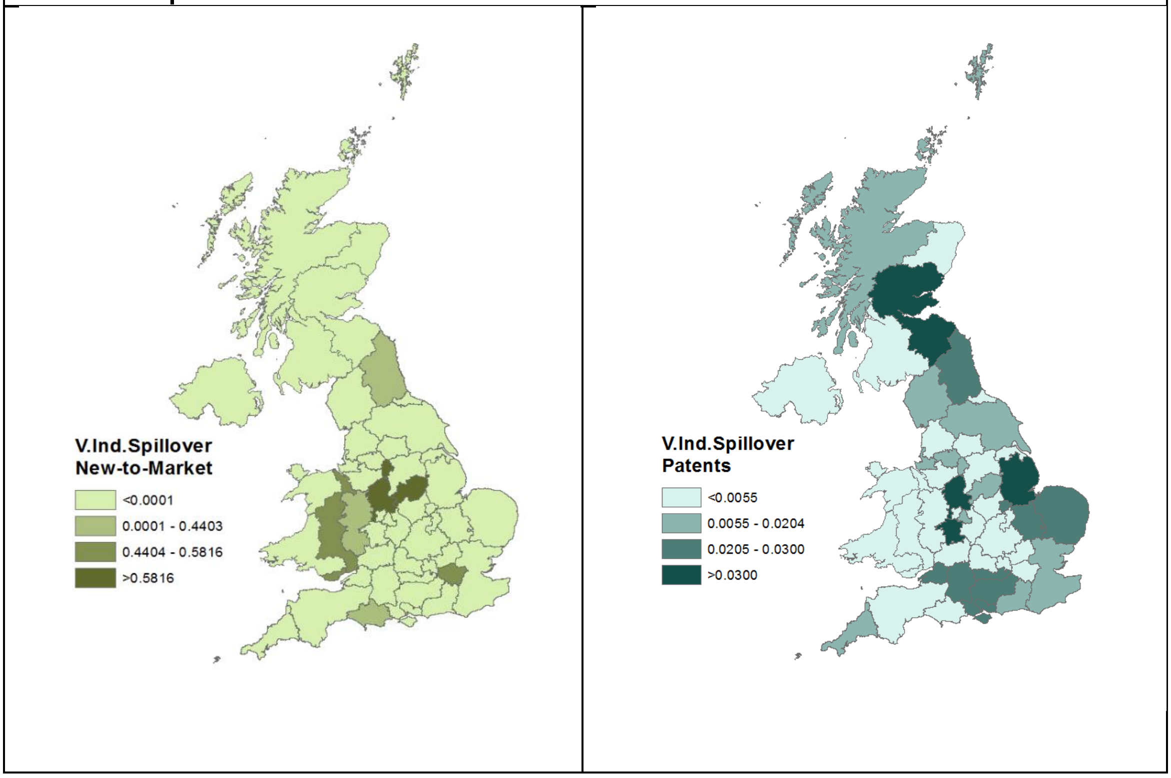
Notes: Estimates based on UKIS and GtR data for the period 2006-2016 using an OLS methodology with firm-wave fixed effects and SIC2 industry and LEP-NUTS2 region time trends. Robust standard errors clustered at the region-industry level reported in parentheses. Additional control variables included in the model: employment, labour productivity, foreign ownership, total R&D investment, stock of patents and exports intensity.

Figure 5: Effect of publicly funded R&D spillovers on firms' innovation output – Regional distribution

A. Horizontal spillovers



B. Vertical spillovers



Notes: Estimates based on UKIS and GtR data for the period 2006-2016 using an OLS methodology with firm-wave fixed effects and SIC2 industry and LEP-NUTS2 region time trends. Robust standard errors clustered at the region-industry level reported in parentheses. Additional control variables included in the model: employment, labour productivity, foreign ownership, total R&D investment, stock of patents and exports intensity.

Table 1: Summary statistics of variables included in the model.

	Number	*Mean*	*S.D.*
Product Innovation	36992	0.225	0.417
Process Innovation	36992	0.139	0.346
Patents	36992	0.020	0.143
Innovation	36992	1.329	7.273
Imitatiom	36992	2.060	8.471
University Spillovers	36992	13.826	4.640
Other Spillovers	36992	13.277	4.350
Horizontal Spillovers	36992	5.094	5.235
Vertical Spillovers	36992	6.997	3.858
Employment	36992	4.074	1.406
Labour Productivity	36992	4.429	1.132
R&D Investment	36992	1.474	2.264
Foreign Owned	36992	0.039	0.194
Age	36992	21.228	11.781
Exporters	36992	0.291	0.454

Notes: Statistics based on UKIS and GtR data for the period 2006-2016.

Table 2: Effect of publicly funded R&D spillovers on firms' innovation output.

	(1) Process Inn.	(2) Product Inn.	(3) Imitation	(4) Innovation	(5) Patents
A. Business to business spillovers					
Horiz. Ind. Spillover	0.00270**	0.000619	0.0374	0.0387**	0.000503
	(0.00131)	(0.00132)	(0.0283)	(0.0194)	(0.000583)
Vert. Ind. Spillover	0.00511	-0.00348	0.0175	0.105	0.00634***
	(0.00652)	(0.00705)	(0.141)	(0.0758)	(0.0022)
B. University to business spillovers etc.					
University Spillover	-0.00114	0.00119	0.0197	-0.0363	0.000616
	(0.00318)	(0.00307)	(0.0592)	(0.0516)	(0.00115)
Other Spillover	0.00114	-0.00101	-0.00951	0.00115	-0.00046
	(0.00344)	(0.00333)	(0.065)	(0.0536)	(0.00127)
C. Control variables					
Employment	0.0122	-0.00064	-0.37	-0.473*	0.00574
	(0.0129)	(0.0147)	(0.347)	(0.261)	(0.00516)
Lab. Productivity	0.0161*	-0.00807	-0.548**	-0.185	0.00138
	(0.0085)	(0.00964)	(0.231)	(0.196)	(0.00427)
R&D Investment	0.0438***	0.0567***	0.546***	0.339***	0.00566***
	(0.00228)	(0.00237)	(0.0487)	(0.0422)	(0.00109)
Foreign Owned	0.0186	-0.0186	0.42	-0.0129	0.0268***
	(0.0184)	(0.0189)	(0.415)	(0.308)	(0.0095)
Age	-0.00327	-0.00550*	-0.0196	-0.105	-0.00044
	(0.00224)	(0.00304)	(0.038)	(0.0666)	(0.00129)
Exporter	0.0390***	0.0727***	0.741**	0.842***	0.0238***
	(0.0126)	(0.0135)	(0.293)	(0.259)	(0.00553)
Firm-Wave FE	Y	Y	Y	Y	Y
Industry*Wave FE	Y	Y	Y	Y	Y
Region*Wave FE	Y	Y	Y	Y	Y
Observations	36992	36992	36992	36992	36992
R-squared	0.117	0.156	0.083	0.070	0.140

Notes: Estimates based on UKIS and GtR data for the period 2006-2016 using an OLS methodology with firm-wave fixed effects and SIC2 industry and LEP-NUTS2 region time trends. Robust standard errors clustered at the region-industry level reported in parentheses. Statistical significance: * p<0.10, ** p<0.05, *** p<0.01. Additional control variables included in the model but not reported: employment, labour productivity, foreign ownership, total R&D investment, stock of patents and exports intensity.

Table 3: Effect of publicly funded R&D spillovers on firms' innovation output – Size distribution

SMALL FIRMS					
	(1) Process Inn.	(2) Product Inn.	(3) Imitation	(4) Innovation	(5) Patents
A. Business to business spillovers					
Horiz. Ind. Spill.	0.00448*	0.00536**	0.071	0.0510**	0.0008
	(0.00234)	(0.00246)	(0.0616)	(0.0257)	(0.000715)
Vert. Ind. Spill.	0.00237	-0.00359	-0.0389	-0.207	0.00525*
	(0.00994)	(0.0132)	(0.330)	(0.198)	(0.00317)
B. University to business spillovers etc.					
University Spill.	0.00296	-0.00452	0.111	-0.183	0.00113
	(0.00560)	(0.00639)	(0.138)	(0.107)	(0.00168)
Other Spill.	-0.00288	0.0037	-0.0986	0.112	-0.00102
	(0.00627)	(0.00673)	(0.147)	(0.104)	(0.00185)
Firm-Wave FE	Y	Y	Y	Y	Y
Industry*Wave FE	Y	Y	Y	Y	Y
Region*Wave FE	Y	Y	Y	Y	Y
Observations	18,810	18,810	18,810	18,810	18,810
R-squared	0.217	0.22	0.184	0.213	0.2
MEDIUM AND LARGER FIRMS					
	(6) Process Inn.	(7) Product Inn.	(8) Imitation	(9) Innovation	(10) Patents
A. Business to business spillovers					
Horiz. Ind. Spill.	0.00253	0.000756	0.0217	0.0272	0.000651
	(0.00162)	(0.00148)	(0.0306)	(0.0387)	(0.000799)
Vert. Ind. Spill.	0.00394	-0.00705	0.0655	0.128	0.00646**
	(0.00911)	(0.00571)	(0.149)	(0.143)	(0.00298)
B. University to business spillovers etc.					
University Spill.	-0.00282	-0.00134	-0.0196	-0.0113	0.00316*
	(0.00413)	(0.00305)	(0.0683)	(0.0779)	(0.00188)
Other Spill.	0.0038	-0.000254	0.0179	0.00549	0.000155
	(0.00445)	(0.00339)	(0.0762)	(0.0830)	(0.00179)
Firm-Wave FE	Y	Y	Y	Y	Y
Industry*Wave FE	Y	Y	Y	Y	Y
Region*Wave FE	Y	Y	Y	Y	Y
Observations	18,182	18,182	18,182	18,182	18,182
R-squared	0.141	0.183	0.101	0.077	0.195

Notes: Estimates based on UKIS and GtR data for the period 2006-2016 using an OLS methodology with firm-wave fixed effects and SIC2 industry and LEP-NUTS2 region time trends. Robust standard errors clustered at the region-industry level reported in parentheses. Statistical significance: * p<0.10, ** p<0.05, *** p<0.01. Additional control variables included in the model but not reported: employment, labour productivity, foreign ownership, total R&D investment, stock of patents and exports intensity. Following the EUROSTAT definition, firms with less than 50 employees are considered *Small* or *Medium-Large* otherwise.

Table 4: Effect of publicly funded R&D spillovers on firms' innovation output – Technological intensity distribution

HIGH-TECH AND KNOWLEDGE INTENSIVE					
	(1) Process Inn.	(2) Product Inn.	(3) Imitation	(4) Innovation	(5) Patents
A. Business to business spillovers					
Horiz. Ind. Spill.	0.00319	-0.00022	0.0648	0.0252	0.000442
	(0.00245)	(0.00244)	(0.0638)	(0.0356)	(0.00123)
Vert. Ind. Spill.	0.0156	-0.00207	-0.00609	0.0138	0.00918***
	(0.0117)	(0.0116)	(0.307)	(0.111)	(0.00330)
B. University to business spillovers etc.					
University Spill.	-0.00572	-0.00499	-0.0122	-0.189	-0.000453
	(0.00421)	(0.00472)	(0.0960)	(0.103)	(0.00200)
Other Spill.	0.00594	0.00351	0.0413	0.148	0.000825
	(0.00494)	(0.00541)	(0.108)	(0.108)	(0.00224)
Firm-Wave FE	Y	Y	Y	Y	Y
Industry*Wave FE	Y	Y	Y	Y	Y
Region*Wave FE	Y	Y	Y	Y	Y
Observations	15,588	15,588	15,588	15,588	15,588
R-squared	0.16	0.198	0.109	0.114	0.206
		LOW-TECH			
	(6) Process Inn.	(7) Product Inn.	(8) Imitation	(9) Innovation	(10) Patents
A. Business to business spillovers					
Horiz. Ind. Spill.	0.00295*	0.00124	0.0208	0.0225	-0.000309
	(0.00168)	(0.00172)	(0.0293)	(0.0268)	(0.000703)
Vert. Ind. Spill.	-0.00435	-0.00325	0.169	0.0874	-0.00231
	(0.00853)	(0.00975)	(0.178)	(0.143)	(0.00421)
B. University to business spillovers etc.					
University Spill.	0.0021	0.00638	0.0339	0.165**	0.00168
	(0.00481)	(0.00453)	(0.0887)	(0.0649)	(0.00164)
Other Spill.	-0.0025	-0.0048	-0.0465	-0.171**	-0.00245
	(0.00510)	(0.00480)	(0.0968)	(0.0711)	(0.00181)
Firm-Wave FE	Y	Y	Y	Y	Y
Industry*Wave FE	Y	Y	Y	Y	Y
Region*Wave FE	Y	Y	Y	Y	Y
Observations	21,404	21,404	21,404	21,404	21,404
R-squared	0.12	0.155	0.089	0.076	0.123

Notes: Estimates based on UKIS and GtR data for the period 2006-2016 using an OLS methodology with firm-wave fixed effects and SIC2 industry and LEP-NUTS2 region time trends. Robust standard errors clustered at the region-industry level reported in parentheses. Statistical significance: * p<0.10, ** p<0.05, *** p<0.01. Additional control variables included in the model but not reported: employment, labour productivity, foreign ownership, total R&D investment, stock of patents and exports intensity. According to the EUROSTAT definition, firms in the following SIC2 (2003) industries are considered *High-Tech*: (24) chemicals and pharmaceuticals; (29) machinery and engines; (30) computers and office machinery; (31) electrical machinery; (32) IT and communication equipment; (33) medical, precision and optical instruments; (34) motor vehicles; (35) transport equipment; (61) water transports; (62) air transports; (64) post and telecommunications; (65) financial intermediation; (66) insurance; (67) auxiliary activities to financial intermediation; (70) real estate; (71) renting of machinery and equipment; (72) computer related activities; (73) research and development; (74) other business activities; (80) education; (85) health and social work; (92) recreational, cultural and sporting activities.

Table 5: Symbolic summary of spillover effects

	Process	Product	Imitation	Innovation	Patents
A. All firms					
Horizontal	+	(+)	(+)	+	(+)
Vertical	(+)	(-)	(+)	(+)	+
University	(-)	(+)	(+)	(-)	(+)
Other	(+)	(-)	(-)	(+)	(-)
B. Small firms					
Horizontal	+	+	(+)	+	(+)
Vertical	(+)	(-)	(+)	(-)	+
University	(-)	(-)	(-)	(-)	(-)
Other	(-)	(+)	(-)	(+)	(-)
C. Medium and larger firms					
Horizontal	(+)	(+)	(+)	(+)	(+)
Vertical	(+)	(-)	(+)	(+)	+
University	(-)	(-)	(-)	(-)	+
Other	(+)	(-)	(+)	(+)	(+)
D. High-tech and knowledge intensive					
Horizontal	(+)	(-)	(+)	(+)	(+)
Vertical	(+)	(-)	(-)	(+)	+
University	(-)	(-)	(-)	(-)	(-)
Other	(+)	(+)	(+)	(+)	(+)
E. Low-tech					
Horizontal	+	(+)	(+)	(+)	(-)
Vertical	(-)	(-)	(+)	(+)	(-)
University	(+)	(+)	(+)	+	(+)
Other	(-)	(-)	(-)	-	(-)

Notes: Derived from Tables 1-3.

ANNEX - DETAILED DATA DESCRIPTION

A.1 Gateway to Research

The version of GtR used here (extracted in early 2017) provides data on all publicly funded research projects over the 2004 to 2016 period, including data from Innovate UK, the seven Research Councils and the National Centre for the Replacement, Refinement and Reduction of Animals in Research (NC3Rs)[17]. Over the 2004 to 2016 period GtR provides information on about approximately 34,000 organizations that participated in publicly funded innovation and R&D projects, including details on the number and value of funded projects, the number and characteristics of partners, the topics and outcomes of the research projects, the value of grants awarded per year, the Research Council providing the funding, and information about each projects' leaders[18]. The GtR data relates solely to the public funding contribution to each project, however, and does not provide any indication of other financial contributions by firms or other organizations.

A.2 The UK innovation survey (UKIS)

UKIS is conducted every two years by means of a postal questionnaire and extensive telephone follow-up survey. The UKIS is the UK contribution to the European Union Community Innovation Survey or CIS.[19] Here, we use data from waves 5 to 10 of the UK Innovation Survey (UKIS) covering the period 2004-2016. Used widely by innovation researchers (see for example, Laursen and Salter 2005; Love et al. 2010; Hall and Sena 2017), the UKIS provides data on a range of aspects of firms' innovation activity and firms' external innovation connections. Questions relating to firm size and structure, customer base, firm product and process innovation activity, the sources of innovation, perceived barriers to innovation, the levels of public support and basic economic information about

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[17] We abstracted the data for this study between the 2nd and the 5th of January 2017 from the Gateway to Research website available at the following link: http://gtr.rcuk.ac.uk

[18] The only public funding for R&D and innovation in the UK not included in GtR regards support provided by the Regional Development Agencies prior to 2010, EU Framework Programmes and support provided by agencies in the Devolved Territories as well as any contributions made by project partners.

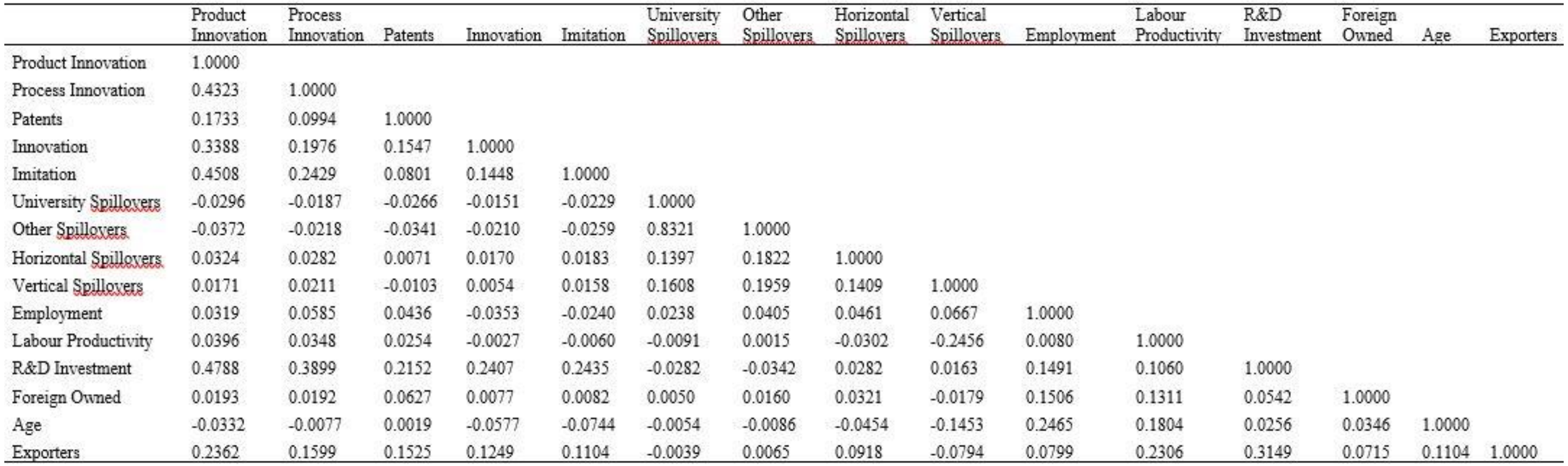
[19] The background and motivation for the innovation survey can be found in the Organisation for Economic Co-operation and Development's (OECD) Oslo manual (OECD, 2005), along with a description of the type of questions and definitions used. In the UK, the Office for National Statistics (ONS) – the UK official government statistical office – manages the administration and data collection for the UKIS.

the firm are also included. The sampling frame for the UKIS is taken from the Inter-departmental Business Register (IDBR), a UK-Government compiled register of all UK businesses based on tax and payroll records. The survey is statistically representative of the 12 regions of the UK, most industrial sectors and firms of all sizes, although firms with fewer than 10 employees are excluded.

A.3 The Business Structure Database (BSD)

The BSD is a compilation of annual snapshots of the UK business population taken from the Inter-departmental Business Register (IDBR). The IDBR itself is compiled using VAT and PAYE records and includes annual turnover and employment data for all UK businesses. The BSD also includes a range of company characteristics including ownership, sector, location etc.

Table A1: Correlation matrix of variables included in the model.



	Product Innovation	Process Innovation	Patents	Innovation	Imitation	University Spillovers	Other Spillovers	Horizontal Spillovers	Vertical Spillovers	Employment	Labour Productivity	R&D Investment	Foreign Owned	Age	Exporters
Product Innovation	1.0000														
Process Innovation	0.4323	1.0000													
Patents	0.1733	0.0994	1.0000												
Innovation	0.3388	0.1976	0.1547	1.0000											
Imitation	0.4508	0.2429	0.0801	0.1448	1.0000										
University Spillovers	-0.0296	-0.0187	-0.0266	-0.0151	-0.0229	1.0000									
Other Spillovers	-0.0372	-0.0218	-0.0341	-0.0210	-0.0259	0.8321	1.0000								
Horizontal Spillovers	0.0324	0.0282	0.0071	0.0170	0.0183	0.1397	0.1822	1.0000							
Vertical Spillovers	0.0171	0.0211	-0.0103	0.0054	0.0158	0.1608	0.1959	0.1409	1.0000						
Employment	0.0319	0.0585	0.0436	-0.0353	-0.0240	0.0238	0.0405	0.0461	0.0667	1.0000					
Labour Productivity	0.0396	0.0348	0.0254	-0.0027	-0.0060	-0.0091	0.0015	-0.0302	-0.2456	0.0080	1.0000				
R&D Investment	0.4788	0.3899	0.2152	0.2407	0.2435	-0.0282	-0.0342	0.0282	0.0163	0.1491	0.1060	1.0000			
Foreign Owned	0.0193	0.0192	0.0627	0.0077	0.0082	0.0050	0.0160	0.0321	-0.0179	0.1506	0.1311	0.0542	1.0000		
Age	-0.0332	-0.0077	0.0019	-0.0577	-0.0744	-0.0054	-0.0086	-0.0454	-0.1453	0.2465	0.1804	0.0256	0.0346	1.0000	
Exporters	0.2362	0.1599	0.1525	0.1249	0.1104	-0.0039	0.0065	0.0918	-0.0794	0.0799	0.2306	0.3149	0.0715	0.1104	1.0000

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