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Assessing innovation spillovers from publicly funded R&D and innovation support: Evidence from the UK

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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. We provide the first comprehensive analysis of the innovation spillovers from publicly funded R&D and innovation support activities in the UK to non-participating firms. Analysis is based on matched data from Gateway to Research, the UK Innovation Survey and the Business Structures Database. Conceptually we differentiate between horizontal (intra-industry), vertical (inter-industry) and university spillovers, each of which have different impacts. We also differentiate between the type of firms impacted by spillovers of each type and their position inside and outside clusters. Both reflect firms' ability to appropriate spillover benefits. Spillovers prove weak in some instances and often limited in scale. 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. Horizontal spillovers effects prove strongest in some rather specific regions, perhaps reflecting the relevance of industrial clustering in mediating knowledge spillovers, while vertical (inter-industry) effects prove more significant across a wider range of areas. Our study sheds new light on the mechanisms through which investment in the public science system has unintended innovation effects.

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. Firms may obtain knowledge for innovation through Research and Development (R&D) and other knowledge creation activities as well as through the type of external knowledge sourcing central to models of open innovation (Audretsch and Belitski, 2023; Torchia and Calabro 2019; Ramirez and Garcia-Penalvo 2018). Firms may also obtain useful knowledge for innovation vicariously or unintentionally, however, through spillover mechanisms such as input-output linkages between firms, social contacts between employees and those in other firms, media publicity or demonstration effects, or through the mobility of employees between enterprises (Roper and Love 2018; Matray 2021).

These spillovers - unpriced and unintentional knowledge externalities – occur because knowledge is 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 et al., 2019). Thus, 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; Lehmann et al., 2022). Spillovers may occur from any R&D or innovation project, however funded, and provide a critical element in the theoretical justification of public support for private R&D and innovation (Arrow, 1962). That is, positive spillovers from publicly funded R&D or innovation projects may generate societal benefits much larger than the private benefits obtained by innovating firms.

In this paper we focus on this critical spillover mechanism, examining the regional innovation spillovers which originate from publicly

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funded R&D and innovation projects undertaken by UK firms, universities and other not-for-profit organisations, and which could then benefit firms closely located within the same region that 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 over the 2004–16 period through UK Research and Innovation (UKRI), the UK Government public agency directing research and innovation funding. 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 research grants publicly funded by UK Research Councils and Innovate UK to the rest of the UK economy. As such it provides new insight into the economy-wide impacts of a key area of UK public investment, which may guide future policy thinking around the benefits of public support to R&D. In more conceptual terms, the analysis extends the argument of Arrow (1962), which justified public investment in R&D on the basis of the spillovers generated, by empirically testing the presence of spillovers from publicly funded R&D, and by identifying which types of spillovers are most significant.

Our analysis makes three main contributions to the existing literature on R&D spillovers. First, we examine which types of innovative activity benefit most from regional spillovers originating from publicly funded university-to-business (U2B) and business-to-business (B2B) R&D collaborations.[2] 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; Byun et al., 2021; Mascarini et al., 2023)). Second, we consider which types of firms not engaged with the public science system benefit most from spillovers from publicly funded R&D, distinguishing between 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 heterogenous strength of spillovers across UK industries and regions, to better understand the nature of these spillovers, and the characteristics of the ecosystems that nurture knowledge externalities from publicly funded projects (Oh et al., 2016; Scarrà and Piccaluga, 2022; Ferreira et al., 2023).

Our results provide general support for the importance of spillovers from the publicly funded science system, while suggesting sectoral and geographic variations in the strength of spillover effects. Taking into consideration different sources of knowledge spillovers, our findings highlight the importance of regional horizontal (intra-industry) spillovers in fostering the adoption of new process and product innovations, while vertical (inter-industry) spillovers have their strongest effects on the development of new patents. University spillovers to firms outside the publicly funded 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 regions, mainly in the South-East of England, 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 regions. Section 7 discusses the key results and Section 8 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.[3] 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; Roy and Paul, 2022), in terms of firms' ability to make use of external knowledge.

Starting from the seminal theories in this field (Marshall, 1920; Arrow, 1962; Jaffe, 1989; Krugman, 1991; Storper and Venables, 2004), 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 from measures of firms' or regions' patenting activity (Furkova 2019). Spillovers are generally proxied by the spatial or sectoral aggregate stock of knowledge, suggesting that firms in the same location (or sector) have access to the same spillovers.

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; De Paris Caldas et al., 2021; Byun et al., 2022; Holl et al., 2022; Myers and Lanahan, 2022; Yano and Shiraishi, 2022), regional (Barra and Ruggiero, 2022; Pereira Dos Santos and Scherrer Mendes, 2021; Furkova 2019; Rodriguez-Pose and Crescenzi 2008; Funke and Niebuhr 2005), or sectoral level (Lee et al., 2017; Audretsch and Belitski, 2022; Kekezi et al., 2022). Byun et al.'s (2021) results, for instance, document the positive effect of technology spillovers on firms' overall innovation outputs. More specifically, the study finds that technology spillovers shift the composition of corporate R&D by promoting innovation based on the exploitation of existing knowledge, while disincentivising innovation that explores new areas and breaks new grounds. Quantifying the magnitude of R&D spillovers created by grants to small firms from the US Department of Energy, Myers and Lanahan (2022) suggest that for every patent produced by grant recipients, three more are produced by others

[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).

[2] While our research, as most existing research in this domain, focusses on the success of research-industry collaborations, Puliga et al. (2023), interestingly, argue that scholars should deepen inquiry into unsuccessful collaborations, as these may also have substantial repercussions in terms of business failures.

[3] For surveys on the effect of public policy on private R&D and innovation, see Zúñiga-Vicente et al. (2014), Becker (2015), Dimos and Pugh (2016).

who benefit from spillovers. Many of these spillovers occur in technological areas that are substantially different from those targeted by the grants. 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).[4] 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).[5] Kekezi et al. (2022) further suggest that the role of short-versus long-distance inter-regional knowledge spillovers in knowledge creation varies greatly across sectors. For the UK, Audretsch and Belitski (2022) show that knowledge spillovers stemming from R&D investment within and between industries have different effects on innovation compared to imitation, and that the ability to access spillovers is conditional on the recipient firm's own investment in R&D. Interestingly, Bernal et al. (2022) find that incoming knowledge spillovers may amplify or limit formal collaboration, but that they only partly substitute formal collaboration in the case of impact on performance.

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, 2009; Storper and Venables, 2004).[6] 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). Focusing on regional patent measures and using data for EU regions over the 2008 to 2012 period, Furkova (2019), for example, identifies significant regional spillovers, even across regional borders. For a sample of German firms, Holl et al. (2022) find, however, that the strength of knowledge spillovers that contribute to innovation persistence in firms attenuates with increasing distance, rapidly vanishing beyond 20/30 km. For the UK, MacDonald and Selmanovic (2023) suggest that only 30% of technologies exhibit localisation, that knowledge spillovers decrease rapidly at geographical distances between 30 and 80 km, and that spillovers within technologies are twice as often localised as spillovers between technologies. Matray (2021) shows that local knowledge spillovers decline rapidly with distance, as spillovers from close neighbouring commuting zones have only limited positive effects, while no effect is found for distant neighbours.[7] Focusing on R&D spillovers from public labs in France, Bergeaud et al. (2022) have shown that both scientific and geographical proximity are important to explain knowledge spillovers from public to private research, in particular when it is driven by direct contracting between public R&D centres and private companies. These effects are mostly significant within commuting zones, with no effect from neighbouring areas, and even within commuting zones the effect of spillovers quickly fades away as distance from public labs increases. All this evidence suggests that this kind of knowledge does not travel well over geographical distances, consequently restricting the possibilities for inter-regional knowledge flows (Asheim and Coenen, 2005; Balland and Rigby, 2017).

Localised knowledge may also have other spatially distinct characteristics, reflecting the presence of specific institutions (typically universities, research labs), clusters of industrial activity,[8] and/or concentrations of specific types of human capital. The characteristics 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 and Piccioni, 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.[9] 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. Wang et al. (2022) find that regions with higher intensity of open innovation could gain more substantial benefits from innovation spillovers. The study's results have policy implications for reducing the inequality of regional innovation capacity. Nonnis et al. (2023) provide evidence of the importance of considering complementarities, such as business process redesign, the co-invention of new products and business models, and human capital investments, for detecting knowledge spillover effects, particularly in the case of domestic spillovers. Foreign spillovers turn out to be less effective, further underlining the view of knowledge spillovers as a mainly localised phenomenon.

A related literature suggests that there is a strong geographical dimension to university spillovers, with evidence of an even stronger spatial decay (Audretsch and Feldman, 1996; Anselin et al., 1997, 2000). Evidence on the spatial boundedness of university spillovers has been gathered 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), and the UK (Abramovsky and Simpson, 2011; D'Este et al., 2013).[10] 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,

[4] With regard to international knowledge spillovers, Eugster et al. (2022) find that foreign knowledge inflows have a growing and quantitatively important effect on domestic innovation. Controlling for the amount of domestic R&D, the study provides evidence that increases in international competitive pressure at the industry level positively affects domestic innovation outcomes. Spithoven and Merlevede (2023) examine the spillover effects of R&D-active domestic firms or foreign-owned firms on total factor productivity of domestic non--R&D-active firms. The study concludes that R&D spillovers generally occur more often than spillovers from foreign direct investment. Wang and Choi (2023) confirm that regions with more effective innovation environments may experience more substantial international R&D spillovers through foreign direct investment or imports.

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

[6] 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).

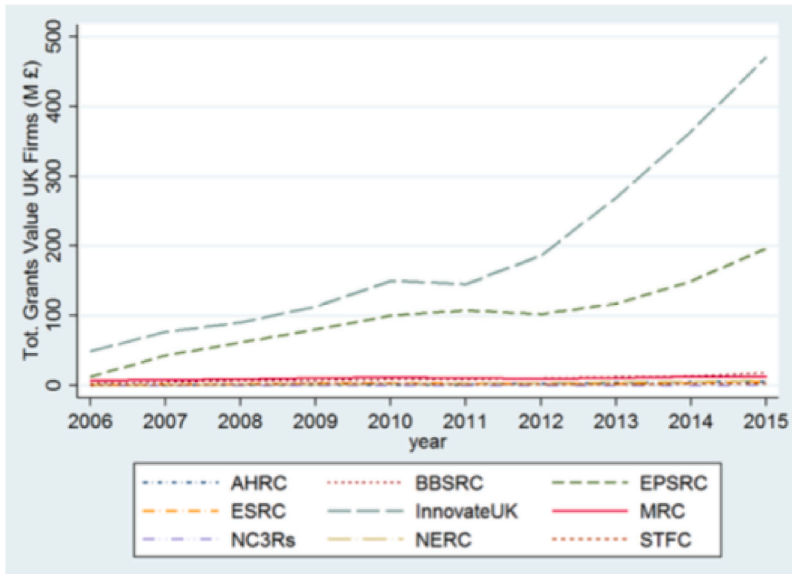
[7] Interestingly, Matray (2021) also finds that local innovation spillovers cause venture capital funds from outside the area to invest more in the local area, and that capital availability amplifies local innovation spillovers.

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

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

[10] Related to this, Østergaard and Drejer (2022), in a study analysing what factors characterise persistent university-industry collaboration on innovation, find that geographical proximity between a firm and a university may facilitate the initiation of a collaboration, although the nearest university is not necessarily the most suitable partner.

(a) Total grant value (£m)



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

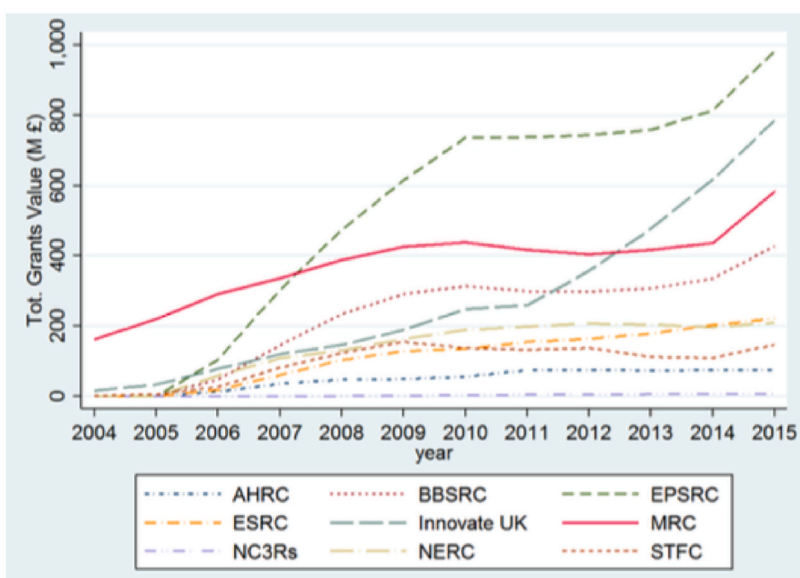


Fig. 1. Evolution of UK Research Council funding.
Notes: Authors' analysis of GtR data for the period 2006–2016.

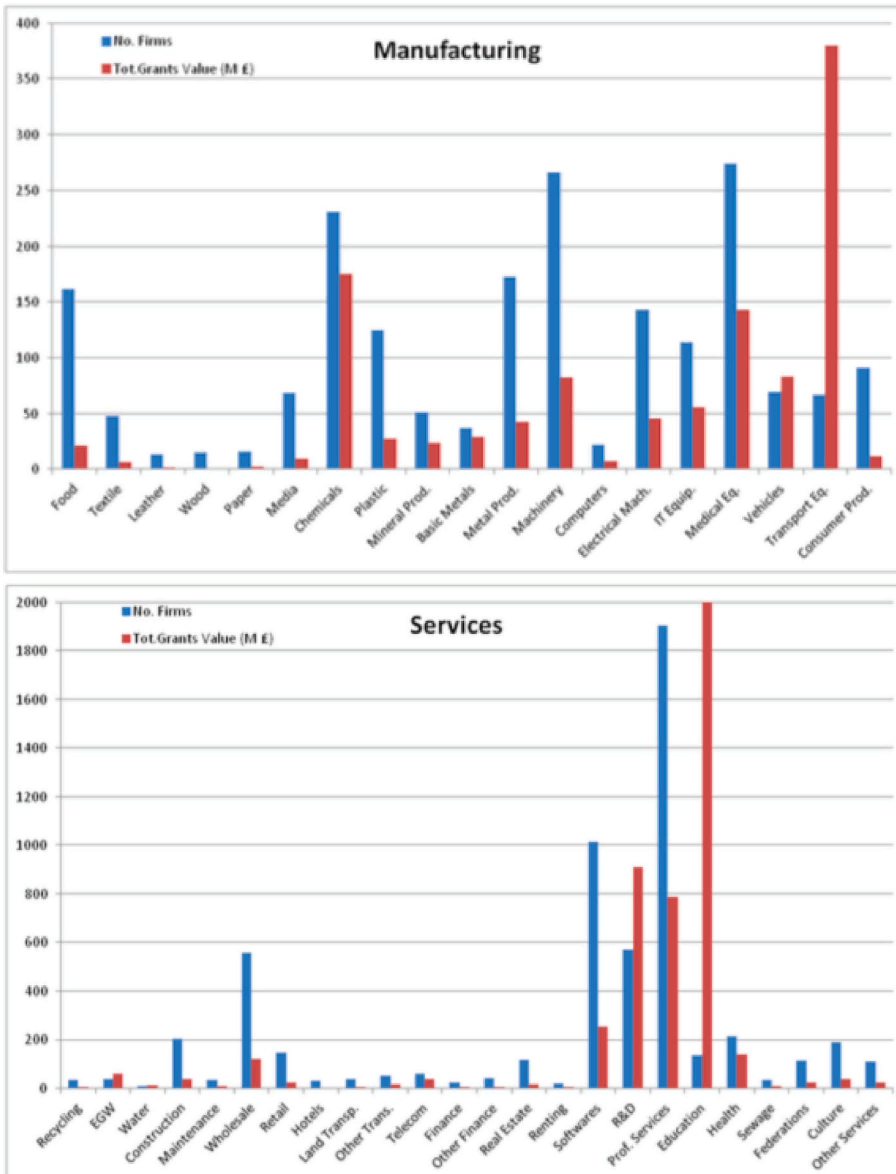


Fig. 2. Industrial distribution of UKRC funded firms.
Notes: Authors' analysis of GtR data for the period 2006–2016.

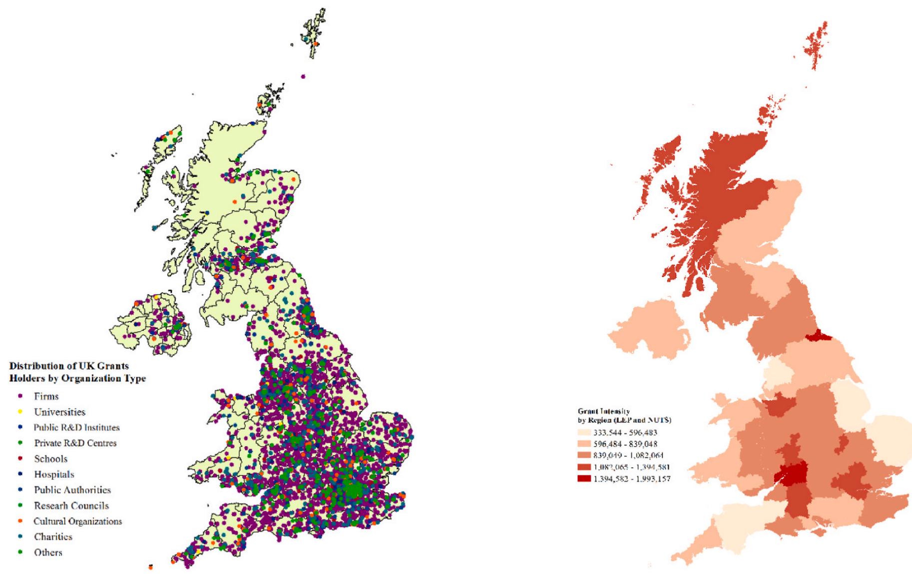


Fig. 3. Geographical distribution of participating organisations and intensity of the funds allocated by UK Research Councils (2004–2016).
Notes: Authors' analysis of GtR data for the period 2006–2016.

especially in industries characterized by knowledge proximity with universities and regions with social trust. Lehmann et al. (2022) further find that university spillovers do not per se have a stimulating effect on firm performance, but that it is the interaction between firms' absorptive capacities and local university spillovers which has positive and significant effects on firms' economic performance. 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 larger companies (Acs et al., 1994) reflecting other evidence of the greater importance of innovation collaboration for small firms' innovation (Vahter et al., 2014).

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 et al., 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 come 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.[11] Building on Bloom et al.'s (2013) framework, Banal-Estañol et al. (2022) find that the negative impacts of rivalry in product markets are mitigated if firms cooperate in research joint ventures, and that such participation allows firms to better absorb technological spillovers and, therefore, create value.

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, where firms introduce radical innovative products which are novel to the market, has very different knowledge requirements from *new--to-the-firm* imitations, innovations that instead are developed for the first time by the company, but are already available in the market from other competitors, and involves very different risks and rewards (Roper and Hewitt-Dundas, 2017). 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, and 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 pursue both knowledge creation and engagement with a broader group of external partners. Engaging with

[11] See Granstrand and Holgersson (2020) for a conceptualisation and new definition of 'innovation eco-system'. Good et al. (2019) review the literature on the technology transfer eco-system, pointing out the great challenges involved with transferring science from universities to the market.

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.

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). Trade-offs 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.[12]

Firms emphasising innovation and imitation will also seek different types of external knowledge (Roper et al., 2022) and may therefore experience different benefits from incoming spillovers. Firms with an orientation towards imitation will prioritise non-interactive learning focusing 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. Regional 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. Regional 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.

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 it will therefore play a moderating role in the relationship between any given level of external knowledge and marketable innovation (Roper and Hewitt-Dundas, 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. Regional 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

[12] 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.

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

	(1)	(2)	(3)	(4)	(5)
	Process Inn.	Product Inn.	Imitation	Innovation	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.

abolished in 2010–12 and replaced with more localised, business-led, Local Enterprise Partnerships (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 (Fig. 1). In 2014–15, Innovate UK funded 1401 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.[13]

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.[14] The most significant Research Council in terms of its business impacts was the Engineering and Physical Sciences Research Council (EPSRC) (Scandura, 2016).[15] 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).[16] Funded projects cover most industries, although there is a concentration in high-tech manufacturing and knowledge intensive services (Fig. 2) and in some more central regions of the UK (Fig. 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

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

[14] 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).

[15] 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.

[16] 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.

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

SMALL FIRMS					
	(1)	(2)	(3)	(4)	(5)
	Process Inn.	Product Inn.	Imitation	Innovation	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)	(7)	(8)	(9)	(10)
	Process Inn.	Product Inn.	Imitation	Innovation	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)	(2)	(3)	(4)	(5)
	Process Inn.	Product Inn.	Imitation	Innovation	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)	(7)	(8)	(9)	(10)
	Process Inn.	Product Inn.	Imitation	Innovation	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.

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 and Innovate UK 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 administrative 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).[17] For the current analysis we use data from the GtR as the source of the potential publicly funded spillovers, considering all R&D funding received by public and private organisations granted by UK Research Councils and Innovate UK.[18] Second, we use data from the UK Innovation Survey (UKIS) to define a range of

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

[18] Not all publicly funded collaborations involve a transfer of funding, but often only in-kind contributions, especially in the case of UK Research Council grants allocated to universities with private partners. However, we use the overall funding allocated to the project as a proxy for the strength of these collaborations and of the magnitude of the potential spillover. Private and public organisations might receive also public support to R&D from regional and international (EU) authorities. However, since 2011 regional R&D funding in England have been substituted by Innovate UK funding at the national level, while are limited to the devolved nations. EU R&D funding have been available until the UK left the European Union, and mostly for universities and other public institutions. Previous studies have shown that EU funding have no significant effect on the innovation probability and success of UK firms. As a consequence, we focus only on national level publicly funded R&D projects, which could be a good indicator of the overall amount of publicly R&D funding across regions and sectors given the highly path dependent nature of this type of funding.

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

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 forms part of a wider survey covering all European countries – the EU Community Innovation Survey or CIS.[19] The UKIS provides data on a range of aspects of firms' innovation activity, including firms R&D input and output measures, the sources of innovation, perceived barriers to innovation, and so on. It includes data on the population of high R&D intensity businesses plus a sample of smaller innovators. The survey is statistically representative of UK regions, industries and of firms of all sizes larger than 10 employees. Given its validity and representativeness, it has been widely used in several innovation studies (see for example, Laursen and Salter 2005; Love et al. 2010; Hall and Sena, 2017). Finally, the ONS Business Structure Database (BSD) covers the whole population of businesses in the UK since 1997 (ONS, 2017) and provides information on firms' age, ownership, turnover, employment, industrial classification at the SIC 4-digit level and postcode[20]. Data from the BSD is used here to structure the analysis and provide a number of firm, region and industry level control variables.[21]

Data access and matching was undertaken through the UK Data Service secured datalab. The data matching process involved a number of steps. First, the GtR dataset provides the names of around 34,000 organisations which participated in R&D grants funded by UKRI. 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 into one of 3 macro categories: firms, universities and public research institutes, and other organisations.[22] For the sample of firms in the GtR dataset we have information on the company name and address details, and for around 80 per cent of them also the Company Reference Number (CRN) identifier. 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. We imported the GtR data into the UK Data Service secured datalab, matching CRNs with the anonymised enterprise reference numbers. This resulted in an anonymised version of the GtR dataset which could then be matched to BSD and the UKIS, creating 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 ever participated in publicly funded research projects.

4.3. Outcome 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, asking whether the firm has implemented in the previous 2 years product/service

[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.

[20] 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.

[21] Information in the Annex provides a fuller description of each of the individual datasets.

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

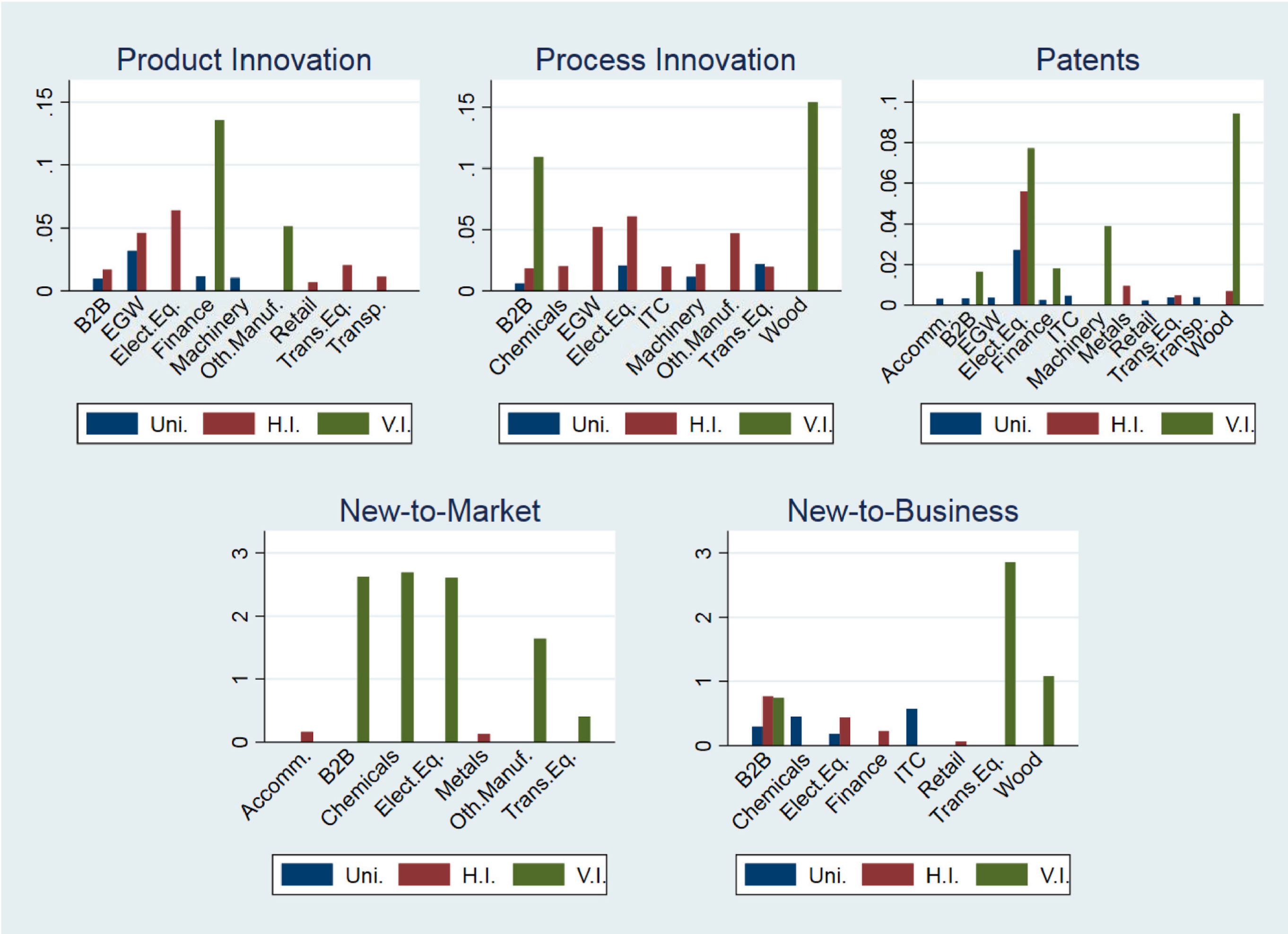


Fig. 4. Effect of publicly funded R&D spillovers on firms' innovation output – Industrial distribution.
Notes: Estimates based on UKIS and GtR data for the period 2006–2016 using an OLS methodology with firm-wave fixed effects and SIC2 industry and LEP-NUTS2 region time trends. Robust standard errors 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.

innovation, thus introducing innovative products or services to their portfolio, or if they implemented process innovation, altering thus their production processes. A third indicator relates to whether firms applied for any patents during the 2 years prior to the date of the survey. 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 across industries. Each of these three 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. Finally, we include two indicators which relate to the novelty of the innovation which firms introduced, and whether these were new-to-the-market innovations, where firms introduced radical innovative products which are novel to the market, or new-to-the-firm imitations, innovations that instead are developed for the first time by the company, but are already available in the market from other competitors. In these two cases, the indicators represent the share of total sales related to new-to-market and to new-to-business innovative products or services adopted in the previous two years, which provide reliable measures of commercialised research outputs.[23]

4.4. Spillover measures

Following the literature previously reviewed, we identify four different channels through which knowledge could spill-over 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** $HOR.IND_{rst}$ following Ornaghi (2006), calculated as the value of R&D grants (GtR_{irst}) received in time period (t) by all firms (i, i=1, …n)

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

participating in publicly-funded innovation projects within the same SIC2 industry (s) and LEP-NUTS2 region (r)[24]

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

Thus, for firms that have never been supported by public R&D grants, this will be equal to the total value of R&D grants received in a given time period by other firms located within the same region and operating in the same industrial sector.

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 **vertical spillovers**, considering the value of publicly funded R&D and innovation grants received by firms in vertically integrated industries located within the same region $VERT.IND_{rst}$. We follow Javorcik (2004) and Du and Vanino (2021) to derive our vertical spillover measure, using the average intermediate demand-supply linkage between SIC2 industry pairs - calculated based on the overall value of intermediate goods transacted between each pair of industries according to 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 funding received by all firms participating in publicly-funded innovation projects in SIC2 sector (p) and LEP-NUTS2 region (r) (GtR_{rpt}) by the relative measure of vertical integration between each pair of vertically integrated sectors (s) and (p) (α_{sp}), and averaging across all vertically integrated sectors (p, p=1, …,P) within each region:

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

As a result, for unsupported firms this will be equal the total value of grants received in a given time period by other firms located within the same region but operating in other vertically integrated sectors, weighted by the overall value of intermediate goods transacted between each pair of industries, and averaged across all integrated sectors. 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 regional spillovers for private firms originating from publicly funded research in universities and other non-for-profit 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 (Frolund et al., 2018). Thus, we build two other measures of knowledge spillover: the first is based on the value of funds (GtR_{urt}) received by **universities and other public research institutes** (u) participating 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 (GtR_{ort}) 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) $OTH.SPILL_{rt}$:

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

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

These two measures will summarise the spillovers coming from non-for-profit organisations located within the same region, as it will be equal the total value of R&D grants received in a given time period by universities and other third sector organisations located within the same region. As a result, we will be able to comprehensively measure both the university-to-business and the business-to-business spillovers originating from publicly funded R&D grants.

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:

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

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 in the previous time period t-1. $UNI.SPILL_{rt-1}$ 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 H1a, 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) regional 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.[25] The link between horizontal spillovers and process

[24] To build our measures of regional spillovers, we consider Local Enterprise Partnerships (LEPs) for England, which are partnerships between local authorities in charge of setting local economic priorities and lead economic growth and job creation within the local area, while using NUTS 2 regions for Scotland and Wales where LEPs are not available, which are similar in terms of aggregation of economically integrated local authorities and population size.

[25] This is somewhat different than Byun et al.'s (2021) result that technology spillovers promote innovation based on the exploitation of existing knowledge and disincentivise innovation that explores new areas and breaks new grounds.

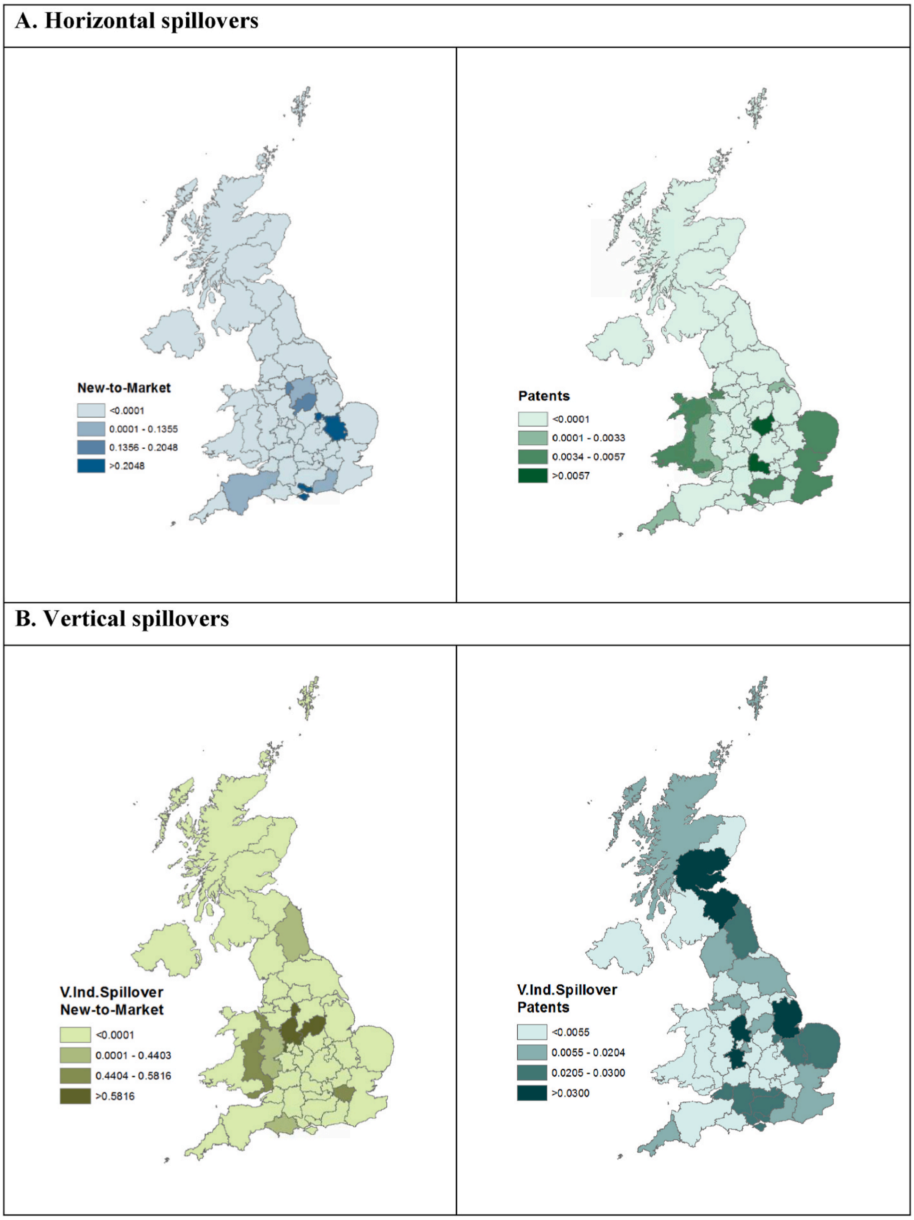


Fig. 5. Effect of publicly funded R&D spillovers on firms' innovation output – Regional distribution.
Notes: Estimates based on UKIS and GtR data for the period 2006–2016 using an OLS methodology with firm-wave fixed effects and SIC2 industry and LEP-NUTS2 region time trends. Robust standard errors clustered 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.

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 stronger 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 firms operating within the same region and sector increases the sales related to new-to-market innovations of firms not participating in government funded R&D projects, by around 0.04 per cent. The small magnitude of this spillover effect is similar to previous evidence on R&D externalities (Bloom et al., 2013; Lychagin et al., 2016; Dimos et al., 2022). 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 vertically integrated firms located in the same region only have a small effect on the probability of patenting by the spillovers-receiving firms.[26] 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; Lehmann et al., 2022). 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 commercialisation of innovations.

Taken together these results provide little support for either hypothesis H1a or H1b. Contrary to expectations, business-to-business spillovers prove most important for process and more radical innovation outcomes.

Hypothesis H2 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 H2 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, for firms' sales due to innovative products (see Table 5).

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 it is 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.[27] 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).[28] 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 H2, 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. Heterogeneity analysis: spatial and industry spillover effects

Our earlier analysis relates to regional 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 Fig. 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 Fig. 5. In each of the maps darker shades represent areas where spillover effects were strongest. Horizontal spillover effects prove strongest in some rather specific regions, 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.

[26] Using US data, Myers and Lanahan (2022) suggest a larger effect - that for every patent produced by grant recipients, three more are produced by others who benefit from spillovers. Many of these spillovers do occur in technological areas that are substantially different from those targeted by the grants.

[27] For an analysis on what factors characterise persistent university-industry collaboration on innovation, see Østergaard and Drejer (2022).

[28] Smaller firms might also lack the absorptive capacity to assimilate this type of knowledge (Lehmann et al., 2022). Larger firms are also more likely to have an R&D department, which is related to Audretsch and Belitski's (2022) finding that the ability to access spillovers is conditional on the recipient firm's own investment in R&D.

7. Discussion

It is clear from previous evidence that firms participating in publicly funded R&D and innovation projects are more innovative (Scandura, 2016) and grow more rapidly (Vanino et al., 2019) than non-participants. Both studies suggest the strong positive and significant effects on firms which are direct participants in publicly funded R&D projects. Here, we consider the spillover effects of these publicly funded projects on innovative outcomes of non-participating firms. As in Vanino et al. (2019), 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 R&D spillovers from publicly funded projects could occur, considering spillovers from local universities, and those from industrially related and geographical proximate private companies.

Our initial hypothesis anticipated that business-to-business spillovers might be stronger on imitation, and that university-to-business spillovers might have stronger effects on innovation. This reflected the potential for different types of knowledge – more leading-edge knowledge in universities – to impact differently on imitation and innovation (Hewitt-Dundas et al., 2019), and the limited prior evidence on the relative effects of spillovers from business-to-business and university R&D (Cappelli et al., 2014). We find little general support for this hypothesis, instead emphasising the impact of business-to-business spillovers on both innovation and imitation and the general weakness of university spillover effects. Our results on university spillovers differ from those of Cappelli et al. (2014) who find positive university spillover effects on innovation. Our results on business-to-business spillovers reflect those of other recent studies which have suggested the limited scale of R&D externalities (Bloom et al., 2013; Lychagin et al., 2016; Dimos et al., 2022).

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). This is consistent with the recent evidence of Myers and Lanahan (2022), which suggested strong spillovers from patents developed by grant recipients to other patenting firms. For firms in low-tech sectors, where patents may be less relevant, we find significant horizontal spillover benefits for process innovation.

One potentially surprising element of our results is the weakness of spillovers from university R&D (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. This contrasts with other international evidence which suggest the significance of spatially bounded university spillovers (e.g. Cardamone, 2018; Segarra-Blasco et al., 2018; Fukugawa, 2017; D'Este et al., 2013). However, reflecting our finding on the significance of university spillovers for high-tech and larger firms, more recent studies (Caloghirou et al., 2021; Lehmann et al., 2022) have emphasised the importance of firms' absorptive or encoding capacity in enabling them to benefit from university spillovers.

Extending our analysis to look at specific industry and spatial patterns suggests 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. This may again reflect higher levels of encoding capacity of firms in these sectors, increasing their capacity to benefit from potential spillovers. Although here we are unable to identify specific aspects of encoding capacity which may be contributing to these stronger spillover effects, previous studies have suggested the potential for cultural (Lucas and Goh, 2009), attitudinal (Agrawal et al., 2010) and structural influences (Johri and Ieee, 2008).

Second, while horizontal (intra-industry) spillover effects prove strongest in some rather specific regions, vertical (inter-industry) effects prove significant across a wider range of geographical areas. This is consistent with suggestions that local clustering of firms within a given industry may be conducive to spillovers mediated through either face-to-face personal contacts or local job changes leading to collective learning (Keeble and Wilkinson 1999; Hummel 2020). Scott and Storper (2015), for example, emphasise the importance of proximity as the source of areas' key economic advantages in knowledge sharing, matching and learning: 'Sharing refers to dense local interlinkages within production systems as well as to indivisibilities that make it necessary to supply some kinds of urban services as public goods. Matching refers to the process of pairing people and jobs, a process that is greatly facilitated where large local pools of firms and workers exist' (Scott and Storper 2015, p. 5). It is also possible that clustering may induce second-round spillover effects as knowledge spillovers in one firm themselves spillover to other proximate or collaborating firms in the cluster.

8. Conclusions

Given prior evidence on the significance of spillovers in a range of contexts, 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 around 6 per cent of the 253,000 UK firms with more than ten employees.[29] 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 results again emphasise the importance of recipient firms' encoding capacity in being able to derive benefits from spillovers (Caloghirou et al., 2021; Lehmann et al., 2022). This has implications for the potential targeting or allocation of public R&D and innovation support where the desire is to generate the greatest social benefits, i.e., strongest spillovers. For example, the strength of intra-industry spillovers seems to be related to local clustering which might suggest targeting support at co-located firms. Sectoral variations in spillovers have also been noted suggesting the potential for sectoral targeting to maximise spillover effects. Few public R&D or innovation funding schemes explicitly consider the potential for such spillovers in their award criteria, however, Commercialisation Australia – a funding scheme to support the

[29] See https://www.gov.uk/government/statistics/business-population-estimates-2021/business-population-estimates-for-the-uk-and-regions-2021-statistical-release-html. Accessed 17th October 2022.

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

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

commercialisation of university research – did include 'National Benefits' (reflecting spillover benefits or knowledge diffusion) as one of its 'Merit Criteria' (Roper and Hart, 2013).

Our analysis is subject to a number of limitations. First, we might not be considering 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.

Data availability

The data that has been used is confidential.

Acknowledgements

The statistical data used here is from the Office of National Statistics (ONS) and is Crown copyright and reproduced with the permission of the controller of HMSO and Queens Printer for Scotland. The use of the ONS statistical data in this work does not imply the endorsement of the ONS in relation to the interpretation or analysis of the statistical data. The analysis upon which this paper is based uses research datasets which may not exactly reproduce National Statistics aggregates. Valuable comments on earlier drafts of the paper were received from the editor and reviewers. Remaining errors are our own.

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)[30]. Over the 2004 to 2016 period GtR provides information on about approximately 34,000 organisations 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.[31] 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 organisations.

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.[32] Here, we use data from waves 5 to 10 of the UK Innovation Survey (UKIS) covering the period 2004–2016. The UKIS provides data on a range of aspects of firms' innovation activity and firms' external innovation connections, its validity and representativeness has been thoroughly document, and for these reasons it has been widely used by innovation researchers (see for example, Laursen and Salter 2005; Love et al. 2010; Hall and Sena, 2017). 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 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.

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[30] 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.

[31] 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.

[32] 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.

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